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Emissions to Air in a Seaport – An Approach to Modelling, Quantification and Reduction

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ABSTRACT

Emission sources associated with port operations are very different and ports are obliged to develop adequate responses. After a general introduction, an overview on literature related to emissions to air in ports and summary of already implemented responses (solutions) on port related emissions, the interdependency between the quantity of CO_2 emitted by mobile harbour cranes during loading process of vessels is modelled, implementing the multiple regression model. Parameters of the model show that 88.53% of the variability of the quantity of the emitted CO_2 to air per vessel depends on selected independent variables. Results presented in this paper enable recognition of some directions of reduction of CO_2 emissions to air by the cargo handling equipment in a port. Furthermore, a planning tool purposed for quantification and forecasting CO_2 emissions from cargo handling equipment in a port, based on a group of relevant parameters, is proposed. In that context, the influence of variations in productivity in the cargo handling process on the quantity of CO_2 emitted to air is analysed. The proposed approach can be implemented in other ports where the diesel-powered cargo handling equipment is in use. In addition, the presented results can be a reliable base for further engagement of the author in this domain.

KEYWORDS

port; emissions; CO_2; modelling; quantification; reduction.

1. INTRODUCTION

The role of the ports has been continuously evolving over the past years. From being multimodal hubs in the supply chain, ports are developing into centres of sustainable energies, clusters of industry and circular economy as well as crucially important pillars of geo-political and geo-economic resilience [1], contributing to the development of the blue economy, too [2]. Ports have crucial importance for the global supply chain [3] and have significant impact on economic activities, both in the country where belong and their wider hinterland [4–9].

Port development frequently appears as a research problem in available references, where different aspects of that topic are considered: modelling port development scenarios, correlation between port development and various influential factors (port competitiveness, port connectivity, economic development of the ports' hinterland, etc.), port-city relations, port regionalisation, port digitalisation, development of a "green port" (port sustainable development), etc. Elements of the development of a "green port" (port sustainable development) researched through available literature are as follows: introducing energy efficiency [10], circular economy transition of ports [11], development of a low-carbon port [12, 13], sustainable development of a port located near the underexploited cultural and tourist capacities [14], incorporating advanced technologies towards sustainable development of ports [15]. In general, the concept called "green port" aims to balance economical and ecological aspects of a port functioning [16].

Development directions/trends of ports are treated in different documents of global importance, too: Sustainable and Smart Mobility Strategy – putting European transport on track for the future [17]: Ports have a great potential to become energy hubs for integrated electricity systems, hydrogen and other low-carbon fuels, and centres for waste reuse and the circular economy; The European Green Deal [18]: calls for a 90% reduction in greenhouse gas (GHG) emissions from transport, in order for the European Union (EU) to become a climate-neutral economy by 2050, working in parallel towards a zero-pollution ambition; The 2030 Agenda for Sustainable Development [19] – adopted by all United Nations Member States in 2015. At its centre are 17 Sustainable Development Goals (SDGs). Some of the SDGs are directly connected with reducing environmental impact of the port area, e.g. SDG13 – climate action, etc. [20].

The objective of this paper the has following principal components, all in accordance with the relevant literature and verified methodology: – to identify, analyse and systematise categories of emissions to air in a port; – to recognise key directions for mitigating risks caused by those emissions; – to define a model of interdependency between the emitted quantity of CO_2 to air from diesel-powered cargo handling equipment (mobile harbour cranes) during the loading/unloading process of a vessel and selected independent variables, using the multiple regression method; – to define some directions of reducing CO_2 emissions to air from cargo handling equipment, directly “generated” from the previously defined multiple regression model of the quantity of the emitted CO_2; – to propose a planning tool for quantification and forecasting CO_2 emissions from cargo handling equipment in a port based on planned throughput structure, mean value of productivity per cargo handling operations and cargo types, average fuel consumption per port machinery types, etc.; – to analyse the influence of productivity in the cargo handling process on the quantity of CO_2 emitted to air from cargo handling equipment;

Through considerations done in this paper all components of the previously mentioned objective are reached. The summary of conclusions enabled by those considerations are as follows (their detailed elaboration is given in the sections related to the discussion of the results and conclusions):

- Emissions from cargo handling equipment belongs to the group of the most critical port related emission sources (mobile emissions sources);
- Adequate response of a port to the emission from cargo handling equipment requires, among other things, appropriate planning and decision making bases (some of them are proposed in the further sections of the paper);
- Pollutants sourced by the cargo handling equipment mainly include particulate matter (PM), NOx, HC, COx, SOx, etc.;
- Carbon dioxide (CO_2) is the most well-known greenhouse gas;
- The defined multiple regression model of interdependency between the quantity of the emitted CO2 to air from diesel-powered mobile harbour cranes (during loading process of a vessel) and selected independent variables shows that (1) the quantity of the emitted CO2 to air is directly proportional with quantity of cargo which is loaded to vessel; (2) the quantity of the emitted CO2 per vessel would be reduced if the number of used mobile harbour cranes is decreased; (3) the quantity of the emitted CO2 per vessel is increasing when the duration of the loading process interruptions caused by internal factors are increasing;
- The optimal option for the reduction of the CO2 quantity emitted to air in a port from diesel-powered cargo handling equipment (mobile harbour cranes) during the loading/unloading process of vessels is a combination of different actions: introduction of electrically-powered port machinery in the loading/unloading process, followed by the optimal utilisation of the effective working time – optimal level of productivity;
- An important question in the previous context is whether the total electrification of cargo handling equipment is feasible (affordable), especially for smaller ports which are, very often, facing lower level of investment capability;
- Implementation of the proposed planning tool for forecasting the quantity of the CO2 emitted from cargo handling equipment in a port and measuring the influence of increased productivity on the emitted CO2 quantity on a concrete case shows that increasing the productivity (quantity of the handled cargo per shift), with the usage of the same resources, is followed by a decreasing of quantity of CO2 emitted to air by the used diesel-powered cargo handling equipment;

After this introduction, section 2 contains a literature overview regarding the emissions to air in ports. Section 3 is related to the existing (already implemented) and planned solutions purposed to reduce emissions to air from principal sources in a port. Results of the research of interdependency between the emitted CO_2 to air from cargo handling equipment through the loading/unloading process of vessels accompanied with discussion of the results are given in the section 4. Within this section a planning tool is proposed for quantification and forecasting CO_2 emitted to air from cargo handling equipment, based on a group of relevant input parameters. Furthermore, in section 4 the influence of variations in productivity in the cargo handling process on quantity of CO_2 emitted to air from cargo handling equipment is analysed. Conclusions are systematised in section 5.

2. EMISSIONS TO AIR – A LITERATURE OVERVIEW

Basically, there are two main categories of maritime polluting emissions: common air contaminants (CAC) and greenhouse gases (GHG), plus an additional group related to other forms of less aggressive pollutants such as dust, smoke, odours and noise [21]. Common air pollutants are [22]: particulate matter (PM10 and PM2.5), ozone (O3), nitrogen dioxide (NO2), carbon monoxide (CO), sulphur dioxide (SO2). The GHG inventory covers the seven direct GHGs under the Kyoto Protocol [23]: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), nitrogen trifluoride (NF_3).

A greenhouse gas (GHG) is a gas that causes the atmosphere to warm by absorbing and emitting radiant energy. Human-made emissions of GHGs from fossil fuels, industry and agriculture are the leading cause of global climate change [24]. Seriousness of the climate changes can be clearly confirmed with the fact that with seven record-breaking months and two record-breaking seasons, 2023 was the world's warmest year in recorded history. According to the EU's Copernicus Climate Change Service, close to 50 % of the days in 2023 were more than 1.5 °C above the pre-industrial average (1850–1900) [25]. Extreme weather events and climate-related natural hazards are becoming more frequent and severe with the rise in the global temperatures [26].

The atmospheric concentrations of GHGs may negatively affect the life on the Earth. Global GHGs emissions per capita, at the global level, have increased by 8.3% between 1990 and 2022 (from 6.24 t CO_2eq/cap to 6.76 t CO_2eq/cap) [27].

Freight transportation and logistics activities contribute 8–10% of global GHG emissions [28]. Breaking down the EU's transport sector emissions, 13.5% is attributed to the maritime sector, 14.4% to aviation and 71% to road transport [29].

In general, the maritime industry contributing to 2–3% of the world's total GHG emissions, prompting initiatives to decarbonise their energy systems and make seaports smarter and greener [30–32]. Emissions from maritime industry can be considered as one of a central issues in reducing the carbon footprint of international trade (along with other pollutants generated by human activities on the planet), which is getting more critical every day [33, 34].

"Fit for 55" refers to the EU's target of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels. It is a legislative package involving the broad policy categories relevant to sustainable mobility [29, 35].

Calculating and reporting emissions to air is a first step [28]. The Global Logistics Emissions Council (GLEC) developed the GLEC Framework, to harmonise the calculation and reporting of the logistics GHG emissions across the multi-modal supply chains [36]. It is the primary industry guideline to support the implementation of the ISO 14083 [37], and can be implemented by shippers, carriers and logistics service providers. The EU is widening and deepening the reporting requirements for the supply chain [38]. EN16258 is a widely internationally accepted CO_2 emission standard for transport and logistics, too [39]. Most of the ports that report CO_2 emissions use their own methods and there is virtually no unified and complete method. This makes comparing results among different ports a difficult task. In the study [34] a tool is proposed to calculate GHG emissions in ports, based on the WPCI (World Ports Climate Initiative), the IPCC (Intergovernmental Panel on Climate Change) guidelines and the GHG Protocol. Carbon dioxide (CO_2) is the most well-known GHG. GHG emissions are often quantified in carbon dioxide equivalents (CO_2eq) [24].

Ports are facing different challenges/risks. Environmental risks can arise at all stages of the port and terminal life cycle [40], including the following [41, 42, 43–45]: emissions from port operations, emissions from ships, dust emissions, dredging, oil spills, chemical contaminants, ballast waters, noise pollution, huge environmental sensitivities, etc.

Climate changes and air quality were the top two environmental priorities in ports in 2023 [46]. There is a significant increase in risks of huge losses in ports due to direct and indirect consequences of the climate changes such as extreme weather events (or some other form of their appearance, like the rise of sea level, etc.). All components of the port, port infrastructure, port superstructure, cargo handling equipment, etc. are threatened, and the consequences can be numerous, with an intense negative impact on the functioning of the port, and the possibility of leading to the interruption of goods flows, which would have clear negative consequences on the level of economic activities in the zone to which the port gravitates. Climate change and the risks they generate make it imperative for ports to establish a management system for those risks with appropriate organisational, technical and all other measures, along with the necessary financial investments, in order to prevent their concretisation (through high additional costs) or to reduce the number of occurrences of unwanted events to a minimum level. In the first European Climate Risk Assessment report [47], carried out by the European Environment Agency (EEA) at the request of the European Commission, the many different economic and social risks are identified that Europe will need to manage over the next decade due to the climate crisis [48]. Managing climate risks is a necessary condition for improving the living standards, fighting inequality and protecting people. For businesses, climate risks are well recognised and are seen as the top four risks in a decade [49]. In general, environmental risks can shape financial stability, impacting economies. Undisrupted environmental and health ecosystems constitute the foundation of the economy [50].

As it was previously written, the European Green Deal [18] calls for a 90% reduction in GHG emissions from transport, in order for the EU to become a climate-neutral economy by 2050, while also working towards a zero-pollution ambition. The way of reaching the defined targets could be very complex. Just for illustration, here is an example. Following the 80th session of the International Maritime Organisation’s (IMO) Marine Environment Protection Committee (MEPC) in July 2023, the revised strategy to reduce GHG emissions from ships includes a commitment to reach net zero “by or around” 2050. The previous target was a 50% reduction in GHG emissions by 2050, compared to the 2008 levels [51]. The disruption in the Red Sea and Suez Canal, combined with the factors linked to the Panama Canal and the Black Sea, and leading to rerouting vessels through longer routes are causing vessel sailing speeds to increase [52], implying increasing GHG emissions for a round trip.

When thinking of sustainability in shipping and ports, most of the focus tends to be on air pollution; however, there are many other areas of importance for green ports such as noise, dust, waste, water pollution, etc. [53].

Emission sources associated with port operations are very different [21, 54, 55] and can be organised into two large groups: the first includes stationary sources such as warehouses, mechanical plants, offices, portable or emergency generators, electricity consuming equipment, refrigeration/cooling equipment etc., and the second includes mobile sources such as ships, cargo handling equipment that is not designed to operate on public roads, transport vehicles that move goods on public roads, smaller on-road vehicles that transport people and supplies, such as cars and vans, railroad locomotives and so on.

Sources can be further divided into emission source categories within each source group. Another emission source type related to port operations is referred to unpaved areas used for cargo or equipment storage. Vehicles and equipment moving through these unpaved areas can disturb the soil surface with winds lifting fine dirt particles into the air [54].

Pollutants sourced by cargo handling equipment (CHE) mainly include particulate matter (PM), NOx, HC, COx, SOx, etc. [56].

In 2013, the European Commission adopted the Clean Air Programme for Europe, with specific measures to achieve the existing air quality targets as soon as possible, and proposals for additional legislation to reduce harmful emissions [57]. It is a clear fact that efforts to make maritime transport less polluting must include ports [58].

Table 1 gives an overview on additional (besides previously mentioned) references related to emissions in ports.

Table 1 – A literature overview

Research problem	Reference
Emissions from ships in ports	
– pollution from ships as a factor that causes significant air and other forms of pollution	[59]
– The international regulations on ship emissions and its influence on the level of the SO_2 emissions from ocean going vessels	[60]
– Pollution of air from large ships in the hub ports	[61]
– The influence of ship emissions of NO_2, SO_2, PM_{10} and $PM_{2.5}$ on air quality in the ports	[62]
– Annex VI (of the MARPOL convention) issues	[63, 64]
– Initial strategy on reduction of GHG emissions from ships in a port	[65]
– Air quality management in some Mediterranean ports	[66]
– Development of infrastructure, regulation and incentives that mitigate shipping emissions in ports	[21]
– Calculation of air pollution inventory in ports	[67]
– Estimation and analysis of ship exhaust emissions and their externalities	[68]
– Estimation of air emissions (CO_2, NO_X, SO_X and PM) released by cruise vessels in ports	[69]
– Initiatives and methodologies that have been undertaken to calculate and reduce emissions and climate change effects in ports	[32, 70-74]
– Estimating trip-specific emissions	[75]
– Developing a method to assess the possible decrease of the emissions from ships in ports, considering human factor influence	[76]
– Monitoring and estimation of air pollutant emissions from ships	[77, 78]
Environmental efficiency of ports	[78, 80]
Estimation of the carbon footprint in ports	[81, 82]
Environmental performance indicators	[83, 84]
Energy management systems in ports	[85]

Source: the Author

In the analysed literature the following research methods are used: inseparable input-output slack-based measure model [79, 80]; ship engines' power method [67]; full bottom-up approach [69]; a meta-analyses scoping review based on the PRISMA-ScR methodology [81]; activity based approach [72]; entropy approach to analysis of environmental performances [84]; Gaussian-Plume dispersion approach [73]; etc. A very wide geographical area is covered by the analysed literature: China [79, 82], Montenegro [67, 68], Croatia [68], Spain [69, 81, 83], Bangladesh [71, 72], Brazil [32], South Korea [80], Thailand [84], USA [74], etc.

3. RESPONSES TO EMISSIONS – SOME CONSIDERATIONS ON SOLUTIONS

There is a need for focused investment in innovative solutions to support the sector de-carbonisation [86], which appears as a relevant driver of the investment projects in ports [1]. Despite the challenges, there are also opportunities for industry to develop sustainable alternatives [87].

In essence, ports are obliged to develop responses to emissions caused by their operations at an appropriate level [88]. It is recommended that ports consider the growing range of innovative systems and technologies that provide integrated solutions to facilitate the reduction of emissions [88]. As modern automated terminals usually achieve high handling efficiency with electric or hybrid equipment, terminal automation is one of the tools to reduce emissions [89]. Many options for air reduction program are available. The selection of the most feasible actions will depend on many factors, such as laws and regulations, terminal set-up, the modal split of the port and the age of diesel engine equipment fleet, etc. [90].

There are already implemented solutions in ports purposed for reduction of GHG emissions. Copenhagen's container terminal has introduced new terminal tractors, rear loaders and industrial trucks within the program HVO100 (HVO – Hydro-treated Vegetable Oil, a type of fuel produced from waste, residue oils and fats, such as used cooking oil). The move will reduce emission of 130t of CO2e/year [91]. HHLA Container Terminal Altenwerder (CTA) in the Port of Hamburg, introduced fully electric automated guided vehicles (AGVs), having now a completely electrified container handling from ship to storage. Exchanging diesel for battery AGVs will avoid the consumption of around three million litres of fossil fuel per year, sparing the environment some 8.0kt/year of CO2 emissions [92].

As the whole industry works towards achieving the agreed upon IMO 2050 targets and having in mind the importance of reduction of ship emissions for achieving those targets, the European Community Shipowners' Association has welcomed the final approval of the Net-Zero Industry Act (NZIA) by the Parliament, the European net-zero emissions proposed in March 2023 by the European Commission to strengthen the production of the technologies needed for decarbonisation [93, 94]. To achieve this, increased emphasis should be put on making affordable clean and safe fuels available and on developing the capacity, access to infrastructure for green maritime fuels [95]. Through the FuelEU Maritime Regulation, the European Commission – with the assistance of the European Maritime Safety Agency (EMSA) – is aiming to increase the use of sustainable alternative fuels in European shipping and ports by addressing market barriers and uncertainty over which technical options are market-ready [96]. Among the multiple fuels and technologies being considered, green methanol and green ammonia, as well as solid oxide fuel cells, liquefied hydrogen, wind-assisted propulsion, air lubrication systems and on-board carbon capture are seen as promising options for achieving the decarbonisation goals set forth by the IMO for the shipping sector [97–99], all in order to achieve an objective of having "zero-emissions vessels" – vessels that emit no GHG or pollutants during their operation [100]. On 12 April 2024, Damen Shipyards Group launched the second of its fully electric RSD-E Tugs 2513, which is being built for the Port of Antwerp-Bruges, Belgium. It was the first fully electric tug to operate in European waters [101].

Additional solutions were developed, which contribute to the better energy profile of a ship: implementation of the schedule optimisation software to reduce shipping emissions by increasing the vessel utilisation rate [102]; a hydrodynamic solution for preventing cavitation occurred during the ship operation (as an influential factor of increased energy usage/reduced energy efficiency) [103];

Regardless of the previously mentioned obvious concrete results in reducing emissions from ships, it is clear that conventional fuels will be around for many years and that shipowners must concentrate on energy efficiency: burning less fuel by design and proper maintenance to maintain efficiency, etc. [104].

Within the port and maritime sector, one of the solutions to reduce emissions in ports is the installation of shore-side electricity (SSE) solutions in ports. However, although the technology is available and fully mature, European ports currently face difficulties in implementing these facilities due to the lack of a harmonised framework on the SSE in the EU ports [105]. Main technical/operational/financial difficulties in planning and implementing the SSE solutions are the cost of installations compared with cost of operation, the cost of electrical power and economic viability of the service, the lack of pricing and taxing framework, the status and capacity of the port electricity grid (power constraints, etc.), the funding sources used to carry out the investments in the ports with the SSE, etc. [106].

Through the numerous EU programs, different projects aiming to achieve sustainable transport solutions were financially supported. 'EfficientFlow', a project co-funded by the European Cohesion Policy between 2018 and 2020, has helped all partners involved in the port call process to optimise their resources and reduce waiting times [107]. The European Union will support 42 projects with more than EUR 424 million of funding for the alternative fuels supply infrastructure. They have been selected under the Alternative Fuels Infrastructure Facility (AFIF) of the Connecting Europe Facility (CEF) [108]. The project REDII Ports, financed under the Interreg North Sea, aims to exploit resources for a technically feasible and economically affordable generation, storage and consumption of cleaner energy and fuels with specific reference to five alternatives: electricity (shore/hydro power/battery), wind//tide/solar, biodiesel, hydrogen, ammonia/methanol [109]. The Norwegian government supported the GASS (Green AI for Sustainable Shipping) research project – a "data driven approach to decarbonisation" enabling shipping companies to identify, analyse and address inefficient energy use on any vessel, in any location, in any weather conditions, in real-time [110]. The EALING project, funded under the Connecting Europe Facility (CEF) programme, aiming at examining and promoting the utilisation of the Shore Side Electricity (SSE) in 16 maritime ports from the Trans-European Transport Network (TEN-T) [111].

It is clear that the role which a port has in implementing the mentioned responses to emissions varies within a wide range, starting from "fully responsible subject" (where a port has the leading role, followed with an obligation to finance related responses) – e.g. providing shore-side electricity solutions for ships in ports; purchasing electric cargo handling equipment; etc. to a “subject who is promoting/initiating/supporting actions“ (a port can launch initiative for implementing a response, but with very limited role in further concrete steps) – e.g. a port can promote (initiate/support related actions) importance of “green ships”, but with no decisive role in fully achieving that objective.

4. QUANTITY OF CO2 EMITTED TO AIR FROM CARGO HANDLING EQUIPMENT: MODELLING

Based on the results of previously made considerations, in this section, focus is on emissions from cargo handling equipment, as one of the most important emission sources in a port.

It is a fact that in the available literature is not presented any approach which starts from “the bottom” – which directs efforts to reduce GHG (CO_2) emission to air in a port through reduction of emissions to air in the basic working process: loading/unloading of a vessel. Having that as an initial motive, here the results of an analysis of interdependency between the quantity of emitted CO_2 (kgCO_2eq/vessel) to air by diesel-powered mobile harbour cranes (during the loading operation of a vessel) and the following independent variables are presented: the quantity of cargo which is loaded in a vessel, the number of the used mobile harbour cranes (MHCs) per vessel and the duration of the loading process interruptions per vessel caused by internal factors (changing positions of the cranes along a vessel, etc.).

In essence, the quantity of the emitted CO_2 during the loading (unloading) process of a vessel is a function of the cargo handling equipment types (and the number of the used items in the process), as well as the time of their effective work. By the type of the used cargo handling equipment, fuel consumption during the time of its effective work is determined, and the length of that time is dominantly defined by the cargo quantity loaded (unloaded) in/from a vessel and the level of productivity during the loading/unloading process of a vessel (t/hour or t/shift or t/24 h or...). Selection of the independent variables is based on these previously mentioned remarks.

Concrete data on which the analysis is based are related to the dry bulk cargo terminal in the Port of Bar (Montenegro), a landlord port with several specialised terminals (besides the already mentioned dry bulk cargo terminal): liquid cargo terminal, container terminal, general cargo terminal, ro-ro terminal and passenger terminal [112].

Additional parameters that describe the object of the analysis are [112]: period – from 2017 to 2021; number of vessels – 39; type of cargo – bauxite; cargo (bauxite) quantity loaded to vessels with diesel-powered mobile harbour cranes – 1,275,058.34 t; cargo (bauxite) quantity loaded to vessels with electrically-powered gantry cranes – 1,257,251.45 t; share of the total quantity of cargo (bauxite) in the total throughput of dry bulks for the period 2017–2021 – 44.6%;

Based on the official data from the Port of Bar information system, the related data series are established, as shown in *Table 2*.

Table 2 – Data series

	y, kgCO2eq	**x1, cargo quantity per vessel, loaded with MHCs (t)**	**x2, number of MHCs per vessel**	**x3, interruptions caused by internal factors per vessel (h)**
1	9,144.28	52,705.90	1	0
2	4,302.92	30,409.12	1	0
3	5,439.42	34,177.94	1	11
4	3,583.17	30,196.93	1	8.33
5	7,260.26	44,497.85	1	0
...				
39	4,788.24	31,305.14	2	0

Source: [112]

4.1 Methodology

Correlation between the quantity of CO_2 emitted to air from diesel-powered mobile harbour cranes and selected independent variables will be established using the multiple regression model.

Regression modelling is a tool for solving multidisciplinary problems with unknown interaction [113]. In the available literature, it was used for carrying out different research: forecasting vessel turnaround time [114], defining correlation between estimated and achieved construction time [115], defining correlations between vessel performances [116], correlations between parameters in the decision making process [117], modelling and assessment of transport services [118], etc.

If *n* is the number of observations of the "Quantity of emitted CO_2 to air" (y), which is a dependent variable, there will be *n* times k number of independent-variable observations (x_{ki}). These observations can be given in a form defined by the following equation [119]:

$$y_i = b_{0i} + b_{1i}x_{1i} + b_{2i}x_{2i} + ... + b_{ki}x_{ki} \tag{1}$$

where i = 1, 2, 3, …… n and b_1, b_2, b_3, …, b_k are the regression coefficients.

In the multiple linear regression, the value of the coefficient for each independent variable indicates the size of the effect the variable is having on the dependent variable, and the sign on the coefficient (positive or negative) indicates the direction of the effect [120]. The multiple linear regression model can be given with a residual part as follows:

$$y_i = b_{0i} + b_{1i}x_{1i} + b_{2i}x_{2i} + ... + b_{ki}x_{ki} + e_i \tag{2}$$

The residual part (e_i) has to be minimal in order to have the best prediction model. It requires the sum of squares of errors (SSE) to be minimal in the regression line. Parameters which describe a multiple linear regression model [113, 117, 120–123] are systematised in *Table 3*.

Table 3 – Parameters which describe a multiple linear regression model

Parameter	Explanation	Equation
The coefficient of determination, R^2	The portion of the variation in dependent variable that is a function of a set of independent variables	R^2 = SSR/SST Where the SSR is the regression sum of squares and the SST is the total of the SSR and the SSE (sum of squares of errors). The SSR is equal to the sum of the squared differences between the predicted value of y and the mean value of y.
Adjusted R^2	Used for comparing two or more regression models that predicts the same dependent variable.	$R^2_{(adj)} = 1 – [(1 – R^2)(n – 1)/(n – k – 1)]$ where R^2 = the coefficient of determination, k = the number of variable, n = the number of data in sample.
Mean squared error (MSE)	Indicates the deviation of observations from the mean. The errors with respect to the mean can be both positive and negative. Errors are squared to remove the negative and then added together.	
Standard error, s	A measure of statistical accuracy of an estimate, equal to the standard deviation of the theoretical distribution of a large population of such estimates. If a coefficient is large compared to its standard error, then it is probably different from 0	$s = [SSE/(n – k – 1)]^{1/2}$ Symbols have the meaning explained before.
F-statistics	The impact of the regression is examined through hypothesis testing: H_0: $\alpha = b_1 = b_2 = b_3 = ... = 0$ – there is no influence of the regression; H_1: $\exists j\ (b_j \neq 0)$, j = 1, 2, ..., k – there is influence of the regression. For passing, the model F-statistic has to be greater than $F_{critical}$. Standard (critical) value of the Fisher test, $F_{critical}$, is defined for: the adopted significance level α = 0.95, the number of degrees of freedom equal to the number of independent variables, the number that represents the difference between n (the number of data in sample), k (the number of independent variables) and the number 1. Therefore, if the calculated value of the F-test is greater than its table values, the null hypothesis is rejected, and the alternative hypothesis that there is an influence of regression is accepted, which means that the analysed parameter b is considered to be significant. If the F-test passes (i.e. the null hypothesis is rejected) in the multiple regression, then it is necessary to proceed to do t-tests. Once it is known that at least one of the independent variables is significant, t-tests can be used to determine which ones are significant.	

t-statistics	The coefficient divided by its standard error. It is determined based on the student's distribution tables for the adopted significance level and number of degrees of freedom n – 2, where n is the sample size. The calculated value of the t-statistics is compared with the value of the t-statistics from the student's distribution tables for the number of degrees of freedom equal to the number of data in the sample reduced by 2 and the adopted significance threshold of 95%. If the estimated value of the t-statistic (its absolute value) is greater than the table value, then the null hypothesis is rejected and the alternative hypothesis is accepted with an error $\alpha < 0.05$ and certainty $1 - \alpha > 0.95$ in relation to regression coefficients b_i.
p-value	It is a standard practice to use the coefficient p-values to decide whether to include variables in the final model. If the p-value is greater than 0.05 (related to the significance level of 0.95), the coefficient is not statistically significant and should be considered for removing. It can be said with a 95% probability of being correct that the variable is having some effect, assuming the model is specified correctly.

Sources: [113, 117, 120-123]

Based on the values of the coefficient of multiple determination, the intensity of correlation between dependent and independent variables in the regression model can be defined by following the Chaddock's scale [122].

The test of the adequacy of the mathematical model is performed on the basis of the ANOVA (Analysis of Variance) technique, which represents the basic statistical technique in the analysis of experimental data [117]. The ANOVA table is presented in *Table 4*.

Table 4 – ANOVA table

Source	df	ss	MS	F-statistic	p-value
Regression	k	SSR	MSR = SSR/(k – 1)	MSR/MSE	
Residual error	n – k - 1	SSE	MSE = SSE/(n – k)		
Total	n - 1	SSTO			

Source: [117]

where k is the number of independent variables; n is the number of data in series; the rest of the parameters have the previously explained meaning.

4.2 Results

The dependent variable, y_i, is the "CO_2 quantity emitted" (by diesel-powered mobile harbour cranes, during the loading of vessels); the independent variables, x_i, are as follows: x_{1i} is "cargo quantity" (loaded, per vessel); x_{2i} is the "number of used mobile harbour cranes" (per vessel), x_{3i} is the "duration of the loading process interruption" (caused by internal factors, per vessel).

The dependent variable – CO_2 quantity emitted, y_i, can be defined as a function of influential factors, x_i:

$$y_i = b_{0i} + b_{1i}x_{1i} + b_{2i}x_{2i} + b_{3i}x_{3i} + e_i \tag{3}$$

where x_i is the independent variable; e_i is the coefficient which represents uncontrollable influences;

Based on the data series established (*Table 2*), the characteristic parameters in the general regression model defined by relation (3) are defined using a statistical software. The mathematical model is as follows:

$$y = 938.3169 + 0.146x_1 – 739.4414x_2 + 33.6735x_3 \tag{4}$$

Parameters of the mathematical model (4) are analysed and the related results are given in *Tables 5–7*.

Table 5 – An analysis of the model's parameters

Predictor	Coefficient	Estimate	Standard error	t-statistics	p-value
Constant	b_0	938.3169	640.0563	1.466	0.1516
x_1	b_1	0.146	0.0104	14.0364	0
x_2	b_2	-739.4414	505.3227	-1.4633	0.1523
x_3	b_3	33.6735	14.9143	2.2578	0.0303

Source: the Author

The estimated values (absolute values) of all coefficients b_i are bigger than their standard errors, which indicates that their values could not be 0 (it indicates that the coefficients are significant).

The value of the t-statistics from the student's distribution tables for 37 degrees of freedom and a significance threshold of 95% is 2.021 [119]. The t-statistics absolute values corresponding to the coefficients b_1 and b_3 are greater than the table value and for them the null hypothesis is rejected, and the alternative hypothesis with error $\alpha < 0.05$ and certainty $1 - \alpha > 0.95$ is accepted. The null hypothesis cannot be rejected for coefficients b_o and b_2.

p-value of variable x_2 – the number of used mobile harbour cranes (0.1523) is bigger than 0.05 (the adopted related significance level is 0.95), and through the following phase of statistical analysis, it will be decided whether to remove them from the model or not [120].

Table 6 – Summary of model overall fit

R-squared	$r^2 = 0.8853$
Adjusted R-squared	$r^2_{adj} = 0.8754$
Residual standard error	831.9907 on 35 degrees of freedom
Overall F-statistic	90.0195 on 3 and 35 degrees of freedom
Overall p-value	0

Source: the Author

Based on the calculated value of r^2 (0.8853) and following the Chaddock's scale [119], as that value is within the range from 0.64 to 1, it can be concluded that correlations between dependent and independent variables are very strong. Based on the calculated value of r^2, it follows that with the regression model (4), 88.53% of the variability of the dependent variable is explained by the joint influence of the independent variables. The rest of 11.47% shows the influence of those factors that are not included in the model (life cycle of diesel-powered cranes, level of skills of operators, eventual usage of other diesel-powered cargo handling equipment, etc.).

Table 7 – Analysis of variance table (ANOVA table)

Source	df	SS	MS	F-statistics	p-value
Regression	3	186,936,748.3315	62,312,249.4438	90.0195	0
Residual error	35	24,227,297.4121	692,208.4975		
Total	38	211,164,045.7436	5,556,948.5722		

Source: the Author

The table value of the F-test, for the level of significance $\alpha = 0.95$ and the number of degrees of freedom 3 (number of independent variables) and 35 (amount of data in the sample – number of independent variables – 1 = 39 - 3 - 1 = 35) is 2.92 [119]. The calculated value of the F-test is 90.0195 and it is greater than its table value, so the null hypothesis is rejected and the alternative hypothesis that there is an influence of regression is accepted.

Taking into consideration that the absolute values of the estimated values of all coefficients b_i are bigger than their standard errors, that the calculated value of the R-squared (0,8853) indicates a strong correlation between dependent and independent variables, that the calculated value of the F-test (90.0195) is greater than its table value (2.92) and that the overall p-value of the regression model (0) is under 0.05 (the related significance level is 0.95), the multiple regression model defined by the relation (4) is adopted as the adequate one and taken as a basis for further analysis.

4.3 Discussion of results

Multiple regression model defined by the relation (4) indicates the following:

- The quantity of the emitted CO2 to air from diesel-powered mobile harbour cranes during the loading process of a vessel is directly proportional with quantity of cargo which is loaded to a vessel if the values of all other variables are kept unchanged;
- The quantity of the emitted CO2 per vessel from diesel-powered mobile harbour cranes would be reduced if the number of the used mobile harbour cranes is decreased (under condition of keeping values of all other variables unchanged);
- The quantity of the emitted CO2 per vessel from diesel-powered mobile harbour cranes is increasing when the duration of the loading process interruptions caused by internal factors are increasing. In a specific way, this correlation suggest the importance of the optimisation of the time utilisation – the reduction of interruptions;

The proposed approach can be generalised and implemented for modelling CO_2 emissions from cargo handling equipment related to seaborne transport in a port, having in mind that total emission of CO_2 from cargo handling equipment during the loading/unloading cargo to/from vessels in a certain period is a sum of those emissions per vessels served in that period.

Based on the previously mentioned modelled correlations between the dependent and independent variables, from the theoretical and practical points of view, some directions of reduction of the emitted quantity of CO_2 from diesel-powered mobile harbour cranes (cargo handling equipment) during the loading/unloading process of a vessel can be defined:

Direction 1: Reduction of cargo quantity loaded/unloaded to/from vessels.

Respecting the fact that the quantity of cargo handled in a port is one of the principal indicators of its market position (the bigger the cargo volume, the better the position of a port on the market), of course, this direction cannot be taken as any basis for reduction of CO_2 emissions to air. It means that permanent efforts have to be made in order to increase the quantity of cargo loaded/unloaded to/from vessels thus improving other indicators of a port's successful functioning (especially port terminal operators): revenue, profit, etc. In parallel, it is necessary to continuously look for acceptable manners of reduction of CO_2 emissions to air. Since the quantity of the emitted CO_2 to air is a function of time – the duration of the loading/unloading process of a vessel (effective time of work of diesel-powered mobile harbour cranes – cargo handling equipment, which is mainly determining their fuel consumption), one of logical directions of action towards reducing the emitted CO_2 quantity is the reduction of working time necessary for loading/unloading the quantity of cargo to/from vessels, without introducing any additional port resources in the working process: to increase productivity in the loading/unloading process of a vessel;

Direction 2: Reduction of the number of diesel-powered mobile harbour cranes used in the loading/unloading process of a vessel.

A simple reduction of the number of used cranes, without a detailed analysis, is not possible for many reasons, and one of the main ones is the necessity to keep the achieved level of productivity in the loading/unloading process (which has to be in line with the contractual obligations accepted by a port). Based on the considerations made in section 3 of this paper, an acceptable concretisation of the Direction 2 can be the replacement of diesel-powered mobile harbour cranes with electrically-powered cargo handling equipment (without any reduction in the achieved level of productivity);

Direction 3: Reduction of the working process interruptions caused by internal factors (changing positions of the cranes along a vessel, etc.).

As this direction considers optimisation of the working time utilisation, too, it is closely connected with the Direction 1 of reduction of the CO_2 emitted to air from diesel-powered mobile harbour cranes (cargo handling equipment), etc.

Summarising all previously mentioned, it is an obvious fact that the optimal option for the reduction of CO_2 quantity emitted to air in a port from diesel-powered mobile harbour cranes (cargo handling equipment) during loading/unloading process of a vessel is a combination of all directions: introduction of electrically-powered cargo handling equipment in the working process, followed by the optimal utilisation of effective working time (increased cargo quantity loaded/unloaded, minimised working process interruptions, etc.). However, the initial question here is whether the total electrification of cargo handling equipment is feasible (affordable), especially for smaller ports which are, very often, facing lower level of investment capability. In this context, it is necessary to point out that the introduction of the electrically-powered cargo handling equipment correlates with higher purchasing costs (in comparison with the diesel-powered equipment with the same capacity) and requires investments in supporting infrastructure. Due to the mentioned low investment capability (caused by different reasons: unstable cargo flows, low revenues, etc.), the „greening“ of small ports is very challenging. Additional elements connected with electrification of the cargo handling equipment contribute to the complexity of the process: changes in required qualifications of the maintenance staff, changes in planning of the port resources (depending on the battery autonomy, etc.), etc. It is an obvious fact that the introduction of the electrically-powered cargo handling equipment, especially in small ports, has to be based on a carefully prepared plan with clearly defined dynamics od actions, defined real financing sources, etc. with a recognised role of all subjects (port authority, port terminal operators, etc.).

Concretisation of the Direction 2 (introduction of the electrically-powered port machinery) would definitely bring the biggest benefits from the aspect of the reduction of CO_2 emissions, but regardless of that, it requires a previous detailed analysis of justification, having in mind, among other things, that the investment costs related to the introduction of the electrically-powered cargo handling equipment (purchasing costs, costs of supporting infrastructure, etc.) are significantly bigger than the costs characteristic for the diesel-powered cargo handling equipment (in the concrete case, mobile harbour cranes). As already mentioned, when considering elements connected with implementation of the Direction 2, it is necessary to have in mind that the level of the productivity achieved by the diesel-powered cargo handling equipment (mobile harbour cranes) does not have to be reduced in order to keep the achieved level of the port competitiveness. Everything related to the electrification of the used cargo handling equipment, thus reducing the quantity of the emitted CO_2 to air, has to be taken into detailed consideration from another specific additional aspect: source of the electric energy used in a port, respecting the key principles of the sustainable development. Namely, if the electric power supply system in a port is based on the non-renewable energy sources, then the effects of replacing the diesel-powered cargo handling equipment with electric items, from the general point of view, are very questionable, having in mind the overall objective of de-carbonisation up to the year 2050 [18]. For example, the share of the electric energy produced from renewable energy sources in Montenegro for the year 2023 was 62.32%, and the remaining 37.68% is from non-renewable energy sources [124]. Respecting this favourable figures, it seems that introduction of the electrically-powered port machinery in the Port of Bar would have positive effects on the fulfilment of the defined national sustainable development goals. It is worthy to point out that the previous statements about the effects of the electrification of the cargo handling equipment (mobile port cranes) are related to only one phase of their life cycle – the phase of exploitation in a port. However, in order to analyse in a more complete way the effects of the electrification of the cargo handling equipment (mobile harbour cranes) in relation to CO_2 emissions (harmful gases) into the air, as well as in relation to other aspects of the environment (waste, etc.), it is important to take into account the phases of the life cycle that precede the phase of exploitation in a port (design, production, testing, etc.), as well as the phases that follow the exclusion of the cargo handling equipment (mobile harbour cranes) from exploitation. If in any of the phases of the life cycle of the cargo handling equipment (mobile harbour cranes) powered by electricity the principle of reducing the emission of harmful gases into the air is not followed, then the overall effects of the electrification are significantly reduced or even almost completely annulated. The mentioned elements directly indicate the complexity of the issue of electrification of cargo handling equipment – from a general level – and the necessity to ensure the optimal fulfilment of goals related to the reduction of harmful gas emissions through the coordinated action of all involved entities (equipment manufacturers, port terminal operators, etc.).

If the mentioned higher costs of concretising Direction 2 (introducing electric cargo handling equipment) in order to reduce emissions to air are taken into consideration, than an approach focused on increasing productivity in the working process through optimal usage of the existing resources could be a reasonable first step with significant potential to result in very concrete effects.

Correlations between the GHG emissions and productivity have been analysed in the available literature, from different aspects, as shown in *Table 8*.

Table 8 – Influence of productivity on GHG emission

Research problem	Reference
GENERAL CORRELATIONS BETWEEN PRODUCTIVITY AND GHG EMISSIONS	
– Influence of productivity on GHG emissions to air;	[125]
– Heat-related labour productivity losses against the costs of climate change mitigation at country and regional levels;	[126]
– Productivity disparities between top and bottom GHG emitters within specific industries;	[127]
– Progress in GHG emissions mitigation (by reducing the working time for employed persons);	[128]
– To what extent cumulative CO2 emissions are linked to increased extreme heat exposure and resulting labour productivity loss across future climate change scenarios;	[129]
– Evaluation of socioeconomic impacts of changes in labour productivity due to heat stress under various climate change scenarios	[130]
– Relationship between weather variables, CO2, share of renewable energy sources, gross domestic product and total factor productivity	[131]
– The change in industrial structure and impacts of carbon emission efficiency on labour and energy inputs;	[132]
– The relationship between a firm's environmental, social and governance performance and labour productivity;	[133]
– Policies that promote productivity growth and financial incentives to decrease emissions;	[134]
– Effects of higher temperatures on the aggregate productivity of modern, diversified economies;	[135]
– The relationship between labour productivity and per capita CO_2 emission;	[136]
– Influence of the greenhouse gas emissions on the productivity of the agricultural sector;	[137]
– Reducing greenhouse gases and reducing other pollutants affecting human health and labour productivity;	[138]
– Hot temperature impact on local labour product and effects in highly exposed industries such as construction, manufacturing and transportation;	[139]
– Effects of global warming on global welfare and economic productivity;	[140]
– Economic and emission linkages and measures of the employment impacts (direct, indirect and induced) of reduced carbon emissions;	[141]
– The relationship between CO_2 emissions, economic growth, available energy and employment;	[142]
– The influence of the digital economy on labour productivity in agriculture;	[143]
– Measure the labour, energy and greenhouse gas emissions footprints	[144]
– The relationship between economic development and carbon dioxide emissions;	[145]
CORRELATIONS BETWEEN THE PRODUCTIVITY AND GHG EMISSIONS IN PORTS	
– The relationship between port productivity and carbon dioxide (CO_2) emissions;	[146]
– The relationship between Shanghai Port carbon emissions and container throughput, energy consumption, number of berths, total foreign trade import and export and net profit attributable to the parent company;	[147]
– Equipment, energy and operational measures for reducing emissions to air in ports;	[148]

Source: the Author

It can be concluded that, among the available literature sources, there are no references that directly examine the influence of increased productivity (with no changes in used resources) and quantity of CO_2

emitted to air from the diesel-powered cargo handling equipment during cargo loading/unloading to/from vessel, which could be generalised on all other cargo handling operations where the diesel-powered cargo handling equipment is in use. This is why the author of this paper was motivated to propose an approach for measuring the influence of increased productivity in the cargo handling process in a port (with no changes in used resources) on the quantity of CO_2 emitted to air from the cargo handling equipment.

In fact, a planning tool is proposed for forecasting the quantity of CO_2 emitted from cargo handling equipment in a port and measuring the influence of increased productivity on the emitted CO_2 quantity. At this stage, the proposed approach is structured as an "excel calculator", whose principal elements, per different productivity levels, are shown in the next tables (*Table 9 and Table 10*).

Productivity level P_0 (t/shift)

Table 9 – Elements of the proposed planning tool – productivity level P_0 (t/shift)

Cargo Group (dry bulk, liquid bulk, general, ro-ro, containers)									
CT_i	**HO_{ij}**	**Q_k (t)**	**P_{0j} (t/shift)**	**S_{P0j}**	**PM_m**	**W_{P0j}**	**N_{PMl}**	**FC_{PMi} (l/h)**	**TFC_{PMi} (l)**
(1)	(2)	(3)	(4)	(5)=(3)/(4)	(6)	(7)	(8)	(10)	(11)=(5)x(7)x(8) x(10)
CT_1	HO_{11}	Q_{11}	P_{011}	S_{p011}	PM_1	$W_{P011-PM1}$	N_{PM1}	FC_{PM1}	TFC_{PM1}
					PM_2	$W_{P011–PM2}$	N_{PM2}	FC_{PM2}	TFC_{PM2}
					...	...	...	...	...
	HO_{12}	Q_{12}	P_{012}	S_{p012}	PM_1	$W_{P012-PM1}$	N_{PM1}	FC_{PM1}	TFC_{PM1}
					PM_2	$W_{P012-PM1}$	N_{PM2}	FC_{PM2}	TFC_{PM2}
	...	...	...	...	...	...	...	...	...
CT_I	HO_{I1}	Q_{K1}	P_{0I1}	S_{p0I1}	PM_1	$W_{P0I1-PM1}$	N_{PM1}	FC_{PM1}	TFC_{PM1}
					PM_2	$W_{P0I1-PM2}$	N_{PM2}	FC_{PM2}	TFC_{PM2}
					...	...	...	...	...
	HO_{I2}	Q_{K2}	P_{0I2}	S_{p0I2}	PM_1	$W_{P0I2-PM1}$	N_{PM1}	FC_{PM1}	TFC_{PM1}
					PM_2	$W_{P0I2-PM2}$	N_{PM2}	FC_{PM2}	TFC_{PM2}
...	...	...	...	...	...	...	...	...	...
$TOTAL_{P0}$:									…

Source: the Author

where:
CT_i = Cargo type (i = 1, 2, ..., I);
HO_{ij} = Handling operation "j" (j = 1, 2, ... J) with cargo type "i";
Q_k (t) = Cargo quantity (t), per handling operation "j"(k = 1, 2, ... K);
P_{0j} (t/shift) = Average productivity per shift (t/shift) in handling operation "j", with cargo type "i" = basic level (mean value, based on the history of data);
S_{P0j} = Number of shifts, necessary for loading/unloading cargo quantity Q_k (t) in handling operation "j" with cargo type "i" corresponding to the productivity level P_{0j};
W_{P0j} = Number of effective working hours per shift, corresponding to the productivity level P_{0j} (mean value, based on the history of data);
PM_m = Port machinery type used in the handling operation (m = 1, 2, ... M);
N_{PMm} = Number of port machinery of type "m" used in the handling operation "j" with cargo type "i";
FC_{PMm} (l/h) = Fuel consumption of the port machinery of type "m" per working hour;
TFC_{PMm} (l) = Fuel consumption of port machinery of type "m" in handling operation "j" with cargo type "i";

Productivity level P_1 (t/shift)

Table 10 – Elements of the proposed planning toll – productivity level P_1 (t/shift)

Cargo Group (dry bulk, liquid bulk, general, ro-ro, containers)									
CT_i	**HO_{ij}**	**Q_k (t)**	**P_{1j} (t/shift)**	**S_{P0j}**	**PM_m**	**W_{P0j}**	**N_{PMl}**	**FC_{PMi} (l/h)**	**TFC_{PMi} (l)**
(1)	(2)	(3)	(4)	(5)=(3)/(4)	(6)	(7)	(8)	(10)	(11)=(5)x(7)x(8)x(10)
CT_1	HO_{11}	Q_{11}	P_{111}	S_{P111}	PM_1	$W_{P111\text{-}PM1}$	N_{PM1}	FC_{PM1}	TFC_{PM1}
					PM_2	$W_{P111\text{–}PM2}$	N_{PM2}	FC_{PM2}	TFC_{PM2}
					...	...	...	...	...
	HO_{12}	Q_{12}	P_{112}	S_{P112}	PM_1	$W_{P112\text{-}PM1}$	N_{PM1}	FC_{PM1}	TFC_{PM1}
					PM_2	$W_{P112\text{-}PM1}$	N_{PM2}	FC_{PM2}	TFC_{PM2}
	...	...	...	...	...	...	...	...	...
CT_l	HO_{l1}	Q_{K1}	P_{1l1}	S_{P1l1}	PM_1	$W_{P1l1\text{-}PM1}$	N_{PM1}	FC_{PM1}	TFC_{PM1}
					PM_2	$W_{P1l1\text{-}PM2}$	N_{PM2}	FC_{PM2}	TFC_{PM2}
					...	...	...	...	...
	HO_{l2}	Q_{K2}	P_{1l2}	S_{P1l2}	PM_1	$W_{P1l2\text{-}PM1}$	N_{PM1}	FC_{PM1}	TFC_{PM1}
					PM_2	$W_{P1l2\text{-}PM2}$	N_{PM2}	FC_{PM2}	TFC_{PM2}
...	...	...	...	...	...	...	...	...	...
$TOTAL_{P1}$:									…

Source: the Author

Productivity level P_2, ... Productivity level P_n

It is obvious that the proposed approach enables partial calculations (not inserted in the previous tables) of the quantity of CO_2 emitted to air (per cargo type, per handling operations, per type of cargo handling equipment, etc.), as well as overall (total) calculations of the quantity of the emitted CO_2 from cargo handling equipment. In *Table 11*, the results of the implementation of the proposed approach are presented, for different productivity levels (measured by t/shift) on a concrete example determined with following parameters [112]:

— Planned throughput structure of the Port of Bar JSC (one out of two port terminal operators in the port of Bar) in 2024;
— All (planned) handling operations with the cargo appearing in the planned throughput structure in 2024;
— All diesel-powered cargo handling equipment used in handling operations with cargo, their fuel consumption, etc.

Table 11 – Results of the implementation of the proposed approach

Product. level	**Annual fuel consumption per cargo handling equipment classes used in the cargo handling process (l)**							**FC (l/year)**	**$FC_{red.}$ (l/year)**	**$kgCO2_{red}$ eq/year**
	MHC	**MH**	**MC**	**WL**	**FL**	**TR**	**TT**			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
P_0 (t/h)	346,371	158,096	2,390	190,008	36,265	33,449	143,823	910,402		
P_1 (t/h) - +5%	329,877	150,568	2,276	180,960	34,538	31,856	136,974	867,050	43,352	99,493.97
P_2 (t/h) - +10%	314,883	143,724	2,173	172,735	32,968	30,408	130,748	827,638	82,764	189,943.04
P_3 (t/h) - +15%	301,192	137,475	2,078	165,225	31,534	29,086	125,063	791,654	118,748	272,526.96

Source: the Author

where MHC is Mobile Harbour Crane; MH is Material Handler; MC is Mobile Crane; WL is Wheel Loader; FL is Fork Lift; TR is Trailer; TT is Tipper Truck; FC is Fuel Consumption; $FC_{red.}$ is reduction in fuel consumption in line with variations in productivity; $kgCO_{2red}$ is reduction in the quantity of the emitted CO_2 from cargo handling equipment;

Reduction of the CO_2 is calculated based on the values of the TTW emission factor (according to the Global Logistics Emissions Council Framework [36]).

Results presented in *Table 11* show that increasing the productivity (quantity of handled cargo per shift), with the usage of the same resources by 5% is followed by a decrease in quantity of CO_2 emitted to air by the used diesel-powered cargo handling equipment by 4.76%, etc. The proposed "calculator" should be used as a useful planning tool in the management of the cargo handling process and general efforts which a port is obliged to make towards its de-carbonisation.

Previously discussed potential directions of reducing CO_2 emission (GHG emission) in a port, as well as other directions not mentioned in this paper, consider the existence of adequate working procedures which can be recognised as one of the initial prerequisites for reducing GHG emissions. In general, optimal procedures can be achieved through the Environmental Management Systems (EMS). The best-known standards, establishing the criteria for an environmental management system (EMS) are ISO 14001 [149] and the EMAS (recommended by European Parliament and the Council of the European Union, 2009) [150]. Standards provide a management framework for reducing environmental impacts and fulfilling legal and other relevant requirements, thus establishing reliable bases for introducing necessary working procedures.

5. CONCLUSION

Considerations done in this paper indicate a level of criticality which emissions to air in a port have and clearly confirm how challenging it can be to reach the related reduction targets especially for ports that are facing s lack of resources and limited investment capability. Regardless on the highest possible criticality of emissions to air, necessary efforts also have to be made in preventing risks connected with all other environmental aspects (water contamination, soils contamination, noise, etc.) – all in order to act towards a sustainable port.

Sources of emissions to air in ports are very different and all of them deserve specific attention, especially emissions from cargo handling equipment which have a significant share in the total port emissions. Based on parameters that characterise the defined multiple regression model of the CO_2 quantity emitted to air from diesel-powered mobile harbour cranes during loading of vessels, some directions of reduction of those emissions are recognised, with the focus on increasing productivity during the loading (unloading) process of vessels through optimised utilisation of the existing resources – reduction of their effective working time, which will be effectuated through reduction of fuel consumption of the engaged cargo handling equipment. Having in mind that electrification is the optimal model and has to be set as a final objective of the efforts of all ports on the way towards their greening, previous directions of actions should be understood as the initial phase of the process with the high level of affordability. Results of considerations are connected with loading/unloading of vessels (seaborne transport), but can be widened to all operations where diesel-powered cargo handling equipment is used. In addition, in this paper a planning toll for forecasting CO_2 emissions from the cargo handling equipment and measuring influence of increased productivity on the quantity of the emitted CO_2 to air is proposed, which could be very helpful in creating a port's emission reduction program in accordance with general objectives defined at the international level ("Green Deal", etc.), respecting all relevant influential factors.

The proposed approach can be implemented (replicated) in all ports where diesel-powered cargo handling equipment is used for loading/unloading vessels. The author plans to continue engagement in this domain giving priority to the research of correlations between variations of productivity in the port working processes where the diesel-powered cargo handling equipment is used and the quantity of CO_2 emitted to air during realisation of those processes, and to further development of proposed "planning tool". Furthermore, the intention of the author is to work on a research related to climate changes as the consequences of the GHG emissions, with the focus on one of their most visible form – adverse weather conditions and their harmful influences on the ports.

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Emisije u vazduh u morskoj luci: pristup modeliranju, kvantifikaciji i redukciji

Deda Đelović

Rezime:
Izvori emisije povezani sa radom luka su veoma različiti i luke su u obavezi da razviju adekvatne odgovore. Nakon opšteg uvoda, pregleda literature koja se odnosi na emisije u vazduh u lukama i rezimea već sprovedenih odgovora (rješenja) o lučkim emisijama, modelirana je međuzavisnost između količine CO_2 koju emituju mobilne lučke dizalice tokom procesa ukrcaja brodova, primjenom modela višestruke regresije. Parametri modela pokazuju da se 88,53% promjena količine emitovanog CO_2 u vazduh po brodu zavisi od izabranih nezavisnih varijabli. Rezultati prikazani u ovom radu omogućavaju definisanje određenih pravaca smanjenja emisije CO_2 u vazduh od lučke pretovarne mehanizacije. Takođe, predložen je alat za kvantifikaciju i predviđanje emisija CO_2 od lučke pretovarne mehanizacije, na osnovu grupe relevantnih parametara. U tom kontekstu, analiziran je uticaj varijacija u produktivnosti u procesu pretovara tereta na količinu CO_2 emitovanog u vazduh. Predloženi pristup se može primijeniti i u drugim lukama gde se koristi pretovarna mehanizacija na dizel pogon. Takođe, prikazani rezultati mogu biti pouzdana osnova za dalja istraživanja autora u ovoj oblasti

Ključne riječi:
luka; emisije; CO_2; modeliranje; kvantifikacija; redukcija.