

Article

Berth Efficiency Under Risk Conditions in Seaports Through Integrated DEA and AHP Analysis

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Abstract

In the context of increasingly complex and dynamic maritime logistics, seaports serve as critical nodes for intermodal transport, energy distribution, and global trade. Ensuring the safe and uninterrupted operation of port infrastructure—particularly berths—is vital for maintaining supply chain resilience. This study explores the impact of multiple risk categories on berth efficiency in a seaport, aligning with the growing emphasis on maritime safety and risk-informed decision-making. A two-stage methodology is adopted. In the first phase, the DEA CCR input-oriented model is employed to assess the efficiency of selected berths considered as Decision Making Units (DMUs). In the second phase, the Analytical Hierarchy Process (AHP) is used to categorize and quantify the impact of four major risk classes—operational, technical, safety, and environmental—on berth efficiency. The results demonstrate that operational and safety risks contribute 63.91% of the composite weight in the AHP risk assessment hierarchy. These findings are highly relevant to contemporary efforts in maritime risk modeling, especially for individual ports and port systems with high berth utilization and vulnerability to system disruptions. The proposed integrated approach offers a scalable and replicable decision-support tool for port authorities, port operators, planners, and maritime safety stakeholders, enabling proactive risk mitigation, optimal utilization of available resources in a port, and improved berth performance. Its methodological design is appropriately suited to support further applications in port resilience frameworks and maritime safety strategies, being one of the bases for establishing collision avoidance strategies related to an individual port and/or port system, too.

Keywords: seaport; berth efficiency; operational risk; technical risk; safety risk; environmental risk

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1. Introduction

Nowadays, ports are a junction of mutual cooperation both within and between countries. They are no longer limited to only a part of the supply chain [1] and contribute significantly to the growth and development of the economy [2]. Global production and trade directly depend on more complex and larger port systems [3]. In addition to their crucial role in the globally integrated supply chain [4], ports have taken a central role as energy hubs. The geo-political landscape, automation, technological advances, changing regulations, and a green agenda are all generating changes in the Maritime Ecosystem,

including ports [5]. Smart ports are born as a strategy to meet customer needs from a technological evolution that generates quality logistical and operational responses [6].

Ports are facing numerous challenges of different nature and intensity of influence: the size and the complexity of the fleet in the shipping sector are increasing [7]; investment life cycles in the ports are becoming shorter [8]; demands for bigger port capacity, followed by the demands for additional port area [9,10]; uncertainties in the economic system that a port serves [11]; the circular economy transformation challenges [12]; importance of hinterland connections, necessity to continuously invest in their improvements and international logistics chains [13]; various sustainability challenges: climate change [14], the pollution generated from port activities [15,16], etc.

The internal (operational, technical, safety, ...) and external (cyber, political, economic, ...) risks faced by the ports are larger and more complicated than ever before [5]. They could lead to disruptive events in the port itself [1,2,17–19], having significant implications for local, regional, and global economies [4,20,21].

Based on a recognized fact that topics related to impacts of different risks categories on port efficiency are only indirectly (partially) treated in the available literature, an objective of this paper is analyzing berth efficiency under risk conditions using the integrated DEA and AHP approaches, and establishing bases for creating strategies for optimal resource utilization, risk mitigation, and port resilience.

After this introduction, Section 2 provides a literature overview of the risk management process in the ports, as well as on the port efficiency. The port where the research was performed is outlined in Section 3. The methodology used is described in Section 4. The results of the analysis of efficiency scores for selected berths (using the DEA CCR input-oriented method) in a port and the intensity of impact of four risk categories (operational, technical, safety, and environmental), using the AHP method, are presented in Section 5. Discussion of the results is in Section 6, giving additional attention to recognizing correlations between the results and maritime safety aspects. Key conclusions of the paper are systematized in Section 7.

2. Literature Overview

2.1. A Literature Overview of the Risk Management System in the Port

The available literature related to the risk management system in the ports is taken into consideration. A summary of the analyzed/researched topics, key findings, and used literature sources is presented in Table 1.

Table 1. Summary of a literature overview of the risk management system in the ports.

Topics Analyzed/Researched	Key Findings	References
Definition of a risk	Risk is the effect of uncertainty on achieving the objectives, often quantified as the Likelihood of the occurrence (L) of an event multiplied by its Impact (I) ($L \times I$). This means that risk can be managed by reducing the likelihood or the impact of the related uncertainty (harmful events: the loss, injury, or other adverse consequences).	[22–31]
Risk management process: definition, phases, objectives	Risk management is a decision-making process that involves identifying, analyzing, and mitigating risk measurement results. Risk management in ports plays an important role in mitigating and preventing possible accidents and disruptions. Guidance for the definition of the risk management process and risk tolerability criteria is referred to as People, Social Context, Environment, Assets, Operations, and Reputation. There is no specific risk management method or framework to cope with all existing and potential threats and hazards in a port.	[32–49]

Table 1. Cont.

Topics Analyzed/Researched	Key Findings	References
Classification of risks	Different approaches to risk classification are implemented, from very general approaches (e.g., internal, external, hidden, or man-made and natural) to a very detailed risk classification in a port.	[1,2,5,17,18,27,36,47,50–61]
Risk probability and severity matrix	Risks can be mapped using a risk severity and probability matrix. It helps ensure that risks receive differentiated management attention and allocated resources. For estimating the occurrence frequency of a risk in a risk matrix, verbal expressions such as very low, low, medium, high, and very high can be used. In addition, to estimate the consequence impact, the following linguistic variables can be used: slight, minor, moderate, critical, and catastrophic.	[18,38,62–66]
Risk registry	A risk registry is a record of risks, current controls, additional required controls, and responsibility for control activities. The process of creating a risk register consists of five steps: setting goals, identifying risks, assessing risks, responding to risks, and monitoring and reporting.	[29,63,67]
Techniques for assessing risks	The methods frequently used for risk assessment are brainstorming, checklists, hazard analysis and critical control, scenario analysis, business impact analysis, failure mode effect analysis (FMEA), failure mode effect and criticality analysis (FMECA), fault tree analysis, cause-and-effect analysis, Markov analysis, Monte Carlo simulation, Analytical Hierarchal Process (AHP) method, . . .	[18,36,46,68–75]
Regulation	Risk management in a port has to be based on the national and international—domain-specific—regulations. In the literature sources used are defined elements of the national (in Montenegro) and international regulations, which are used as a base for the structuring and functioning of a risk management system in the field of safety and health at work.	[76–88]

(source: authors).

Each category of risks, present in a port (terminal), has its own characteristics, which are determined by numerous factors: the role of the port in the belonging port system, the functions of the port, the level of specialization of the port, the characteristics of cargo that appear in the throughput structure (participation of dangerous cargo, . . .), types of cargo handling operations with cargo, etc. In the context of risk management, it is important to point out that risks are changing over time (and their potential negative impacts are changing depending on time), that they are interconnected (very often one risk arises from another, with possible greater intensity) and, in the absence of adequate mitigation measures, have synergistic effects.

Results of the considerations made indicate that different risk categories exist in all phases of the port life cycle (design, building, exploitation, . . .). Although numerous options of risk categorization were presented in the available literature, some important risk categories characteristic of ports were not explicitly identified. Here are proposed examples of some “additional” risk categories:

- dependence of strategic long-term contracts on rented resources (warehouses, port machinery, . . .);
- difference between the purpose of the area defined by the spatial planning documentation for the port area and the character of the activities performed in that area;
- development of alternative (competitive) logistic routes which could attract cargo passing through a concrete port or cargo from that port’s hinterland area;

- a delay in fulfilling preconditions to serve ships in accordance with the ongoing development trends in the shipping industry: absence of on-shore power supply connections and lack of facilities for supplying ships with alternative fuels. In general, a delay in adjusting business activities in a port to changed national and international regulations, etc.

It should be noted that the top risks identified in the maritime industry (including ports) for the year 2022 were political instability, financial instability, and cyber-attacks [62].

The available literature considers various aspects of risk management in ports/terminals (container terminals [27,37,40], ro-ro terminal [36], coal terminal [37], ...), as well as the risk management in the logistic chain as a whole [3,4] or some of its “other” elements (customs [43], ships [89], ...). The priority is given to the structure of the risk management process, risk classification, and recognition of their criticality ranks, etc. The results presented enable clear conclusions about the highest importance rank of risk management in the ports for their daily functioning as a crucially important link of a logistic chain and their sustainable development, enabling concretization of all of their functions, as intermodal, production, trade, and energy production and distribution hubs. As well, the available literature confirms that the adequate functioning of the risk management system (fulfilling its objectives) requires engagement of port resources and generates costs.

Although a very wide group of topics is in the available literature on risk management in the ports, there is a lack of references related to the impacts of risks on efficiency in a port. It is a main reason for selecting the central object of research of this paper: to analyze efficiency scores for selected berths in a port, using the DEA CCR input-oriented method, and to identify the intensity of impacts of different risk categories on berths’ efficiency by the AHP method. Research is performed in the Port of Bar (terminal operator Port of Bar JSC, terminal for dry bulk and liquid bulk cargo), for the period from 2021 to 2024.

2.2. A Literature Overview of Port Efficiency

Port efficiency is the capability of a port (terminal) to fit the optimum number of inputs to a given output level [90]. Port efficiency can be defined as (i) a benchmark of best practices and (ii) observable gaps between what a port currently produces and what it would optimally produce [91].

A group of crucially important tasks in the port management process is related to achieving a greater degree of efficiency. It could be achieved through different actions: improving the qualifications of the workers [91,92], technological improvements [93], etc.

The efficiency of port operations directly influences the speed, cost, and reliability of global shipping [94]. Port efficiency depends on different influential factors: the various technological advancements, including digitalization, advanced analytics, and sustainable technologies [94], adaptation to climate change (especially for the coming years) [95], privatization strategies of core port operations [96,97], security procedures according to the ISPS Code [98], the design of ports, including traditional facilities and smart port designs with automated machinery [99]. Port efficiency was researched in some additional references, too, as shown in the next table (Table 2).

Table 2. Additional references on port efficiency.

Object of Research/Findings	Reference
Object of research: A new methodology to quantify the efficiency dynamics of a port over time. Findings: An optimization-based approach for efficiency measurement under uncertainty and a risk-based index to measure the efficiency of any operating unit.	[100]

Table 2. *Cont.*

Object of Research/Findings	Reference
Object of research: Risk management in the maritime supply chain. Findings: When supply chain risk increases, efficiency significantly goes down, even when the maritime supply chain is very good.	[101]
Object of research: The importance of port efficiency and service quality. Findings: Exporting firms have a positive willingness to pay for a reduction in the handling time. Findings emphasize the importance of trade facilitation measures in improving port efficiency and service quality.	[102]
Object of research: Determinants of effective high-risk cargo (HRC) handling at seaports. Findings: The study confirmed the correlation between HRC training and the level of knowledge of risk mitigation and emergency procedures, documentation understanding, and regulations adherence.	[103]
Object of research: Impact of port efficiency on a nation's ability to compete internationally. Findings: Port terminal efficiency and the quality of services are the most important factors in selecting a container terminal, followed by port charges, hinterland connections, and port location.	[104]

(source: authors).

In general, there are three required elements for measuring efficiency in ports: decision-making unit (DMU), input variables, and output variables [90]. In the available literature related to measuring port efficiency, different methods (techniques) are used: original least squares (OLS), corrected original least squares (COLS), data envelopment analysis (DEA), stochastic frontier analysis (SFA), etc. [105].

Efficiency in a port can be measured in different ways using various metrics: efficiency of a whole port (in comparison with other ports), efficiency of terminals in the same port or among different ports, efficiency of berths within a terminal, etc.

3. Description of a Port Where the Analysis Is Performed

The Port of Bar [106] is a multipurpose port, situated at the south of the Adriatic Sea, established at the beginning of the last century (1906). The Port is managed according to the landlord port management model. Within the Port area are two functioning terminal operators: Port of Bar JSC, where the major shareholder is the State of Montenegro, owning 78.55% of shares, and the Port of Adria JSC, where the majority of shares—62%—are owned by the Turkish company, Global Ports Holding. There are several specialized terminals in the Port of Bar: a terminal for dry bulk and liquid bulk cargo, a container terminal, a general cargo terminal, a ro-ro terminal, and a passenger terminal.

The concrete results presented in this paper are related to the terminal for liquid bulk and dry bulk cargo, managed by the terminal operator Port of Bar JSC. Basic characteristics of the terminal are given in Table 3.

Positions of the berths at the terminal for liquid and dry bulk cargo are shown in Figure 1.

Table 3. Characteristics of the terminal.

Volujica Quay—berths: 01, 02, 03	Total length: 555 m; individual length of berths: 185 m; Water depth: 14 m
Old Quay—berths: 04, 05, 06	Total length: 280 m; individual length of berths: 93 m; Water depth: 5 m–7.2 m;
New Tanker Berth–07 (NPV)	Maximum ship's LOA: 200 m; Water depth: 13.5 m

(source: [106]).

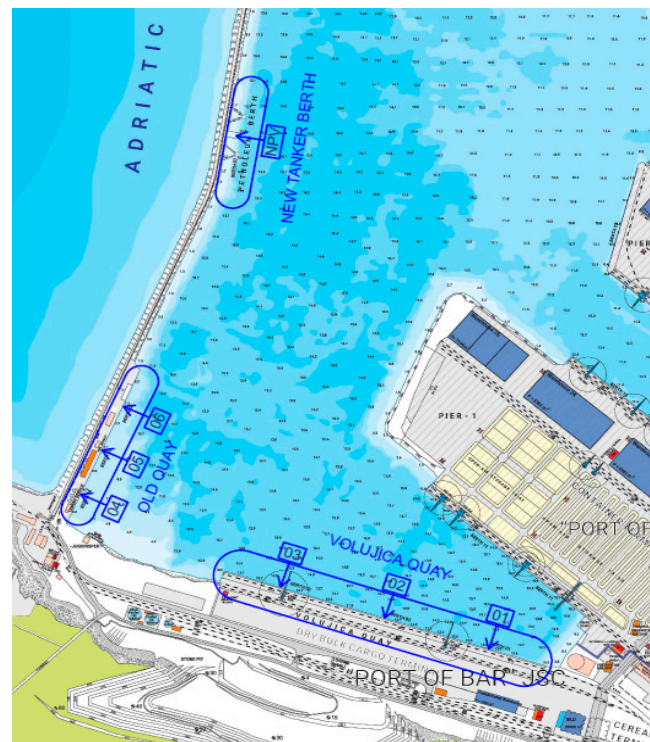


Figure 1. Positions of the berths (source: authors).

4. Methodology

Considerations performed in this paper are based on the following two-stage methodology: the first is defining efficiency scores for selected berths at the terminal for liquid bulk and dry bulk cargo using the DEA CCR input-oriented method, and the second is to define the intensity of the impact of different risk categories on the efficiency scores by the AHP method. These two phases are interconnected: the same input variables for defining the efficiency scores in the first phase, using the DEA CCR input-oriented method, are used as criteria—variables for the level 1 of the hierarchy model are established for defining the intensity of the impact of risks on berths' efficiency in the second phase, using the AHP method. The input-oriented method is used, bearing in mind that minimizing input resources (number of workers/labor or equipment or costs) may be more relevant than maximizing output(s) when efficiency is being evaluated under resource constraints.

4.1. Data Envelopment Analysis (DEA)

Data Envelopment Analysis (DEA), developed in 1978, is a linear programming-based method for evaluating the performance of organizational units called decision-making units (DMUs) [91,93,107–110]. There are two basic DEA models, DEA-CCR (Charnes–Cooper–Rhodes) and DEA-BCC (Banker–Charnes–Cooper) [105]. The DEA approach has been used in numerous domains, including ports [90,105–107,110–113].

The DEA-CCR model has two versions: the first is input-oriented, and the second is output-oriented. The objective of the first is to minimize inputs for reaching outputs, while the second attempts to maximize outputs [105,114,115].

The original DEA-CCR model problem formulation for assessing efficiency was defined as a task of fractional programming (FP), while the solution procedure consists of linear programming (LP) usage for each of the units under assessment [115]. The mathe-

mathematical interpretation of the DEA-CCR model for the chosen entity “o” follows [110,115]—Equations (1)–(4).

$$(FP) \max \theta = \frac{\sum_{r=1}^p u_r y_{r0}}{\sum_{i=1}^m v_i x_{i0}} \quad (1)$$

$$\frac{\sum_{r=1}^p u_r y_{rj}}{\sum_{i=1}^m v_i x_{ij}} \leq 1, \forall j = 1, 2, \dots, j_0, \dots, n \quad (2)$$

$$u_r \geq 0, r = 1, 2, \dots, p \quad (3)$$

$$v_i \geq 0, i = 1, 2, \dots, m \quad (4)$$

where y_r —outputs; x_i —inputs.

As for the relative efficiency θ of one DMU “o”, the maximum of function (1) is an objective, and taking into account the condition (2), the conclusion that $0 \leq \theta \leq 1$ for each DMU_o is clear. In addition, the weight values may have variations from one DMU to another, and the calculation of weights (v_i) and (u_r) maximizing the ratio of DMU_o is the objective of each evaluated DMU. On the other side, if the relation (2) is true for every DMU, each of them belongs to the efficiency frontier beyond it. When $\max \theta = \theta^* = 1$, that indicates the achievement of efficiency and means that DMU_o is efficient. The case when $\theta^* < 1$ means that DMU_o is inefficient [115]. The fractional problem (FP) is non-convex, nonlinear, has a linear and fractional objective function and constraints, and is replaced by the following linear programming problem (LP_o). These two problems are equivalent; thus, the DEA-CCR basic model can be defined with the following relations [110,115]—Equations (5)–(9).

$$(LP) \max \theta = \sum_{r=1}^p u_r y_{r0} \quad (5)$$

$$\sum_{i=1}^m v_i x_{i0} = 1 \quad (6)$$

$$\sum_{r=1}^p u_r y_{rj} - \sum_{i=1}^m v_i x_{ij} \leq 0, (\forall j = 1, 2, \dots, n) \quad (7)$$

$$u_r \geq 0, r = 1, 2, \dots, p \quad (8)$$

$$v_i \geq 0, i = 1, 2, \dots, m \quad (9)$$

where y_r —outputs; x_i —inputs.

4.1.1. Identification of the Decision-Making Units (DMUs)

Decision-making units (DMUs) are berths (seven berths) at the terminal for dry bulk and liquid bulk cargo in the Port of Bar JSC (Table 4).

Table 4. Decision-making units (DMUs).

DMU _i	Purpose/Main Activities Carried Out
DMU ₁ —berth 01	loading/unloading operations with dry bulk cargo (grain, bauxite, salt)
DMU ₂ —berth 02	loading/unloading operations with dry bulk cargo (copper concentrate, coal, iron ore)
DMU ₃ —berth 03	loading/unloading operations with dry bulk cargo (crushed stone, iron scrap)
DMU ₄ —berth 04	unloading operations with dry bulk cargo (cement in bulk)
DMU ₅ —berth 05	loading operations with liquid bulk cargo (acetic acid)
DMU ₆ —berth 06	loading/unloading operations with liquid bulk cargo (oil derivatives)
DMU ₇ —berth 07	unloading operations with liquid bulk cargo (oil derivatives)

(source: authors).

4.1.2. Selection of the Input and Output Variables

The assessment of port efficiency using the DEA method requires the adequate selection of input and output variables [116]. The most frequently used inputs are resources such as land, human resources, and equipment, as well as the total quay length (m); net berth productivity (t/h); operation costs; maximal allowed ship draft (m); etc. [91,105,112,116–119]. The measurement of the output is performed by throughput (t), terminal capacity (t), number of ships, number of passengers, number of containers, berth occupancy, vessel turnaround time [105,112,116,117,119], etc.

There is no universal rule (no consensus) on the selection of the input/output variables, which could be recognized from the available literature [116,120]. In the following parts of this section, DMUs, input/output parameters, and the period are taken into consideration.

Input variables: number of workers directly engaged in the cargo handling process, N_w ; berth length, B_l (m); water depth (by the berth), D_w (m); operation costs, C_o (EUR).

Description of the input parameters follows.

Number of workers, N_w —Workforce is of the highest importance for the efficiency and productivity of a port, as well as for the safety and security of its operations. A shortage of skilled workers impacts cargo handling operations and the competitiveness of a port [121]. The factors that influence the performance of workers in a port include [122,123] challenges in optimization, technology and automation use, regulatory framework, job safety, etc.

It is a general fact that all employees in a port have responsibilities in the domain of risk management, according to the character of their workplace and in line with the relevant working procedures. The level of those responsibilities varies within the range from more than 0% to less than or equal to 100% and is related to the following: all employees are obliged to identify risks when performing their working tasks; all employees are obliged not to contribute to an increase in the level of risks when performing their working tasks; all employees are obliged to reduce risks to the As Low As Reasonably Practicable (ALARP) level or to completely eliminate risks when performing their working tasks; all employees should strictly take into account that they do not generate new risks through their work engagement.

Essentially important prerequisites for the appropriate concretization of the aforementioned duties of employees from the domain of risk management are the existence and application of adequate working procedures, the optimal level of training of employees for the implementation of tasks from the scope of duties of the workplace, and an adequate level of awareness regarding the importance of the risk management system.

In order to calculate efficiency scores for defined DMUs (berths), data on the number of workers directly engaged in the cargo handling process by berths and years from the analyzed period are systematized based on the official data from the Port Information System [106]. The number of engaged workers mainly depends on cargo type (defined in Table 4), type of the cargo handling operation (defined in Table 4), cargo quantity handled/cargo throughput in the analyzed period, level of productivity per shift, etc. In the group of engaged workers are some who have tasks only from the domain of risk mitigation (reduction or elimination of risks): e.g., signal man (who is assisting the crane driver), fireman (prevention during the handling operations with dangerous cargo, . . .), etc.

Berth length, B_l (m)—The ability to provide a berthing space for a vessel without delay is one of the major managerial concerns in a port, and the determination of the optimal quay length is a task of the highest priority [124]. In the available literature, quay length was taken into consideration from different aspects: a new extension of the berth and quay cranes allocation and scheduling problems considering worker performance variability and yard truck deployment constraints [125], solutions which integrate continuous berth allocation, quay crane assignment, and on-shore power supply allocation [126], how to

optimize the berth and crane allocation and to minimize the overall service time for the ships and to improve the utilization of the terminal assets [127], the optimal allocation of ships to quay length at a container terminal in a port [128], etc.

The level of availability of berths directly affects the possibility of maintaining the continuity of the cargo handling process in a port. There are two basic situations that limit the use of the berths (quay).

The first one is related to its maintenance. Namely, it is necessary to carry out the activities of the berths' (quay's) preventive and corrective maintenance in order to keep the parameters of its condition in the zone of permissible deviation and to reduce, up to the absolute minimum, all risks connected with the inadequate condition of the berths (quay). During the period of realization of maintenance activities, part of the operational quay may be out of operation. That, in a certain time interval, reduces the reception capacity of the operational quay, which is directly conditioned by risk-related activities (maintenance activities).

The second characteristic situation, generated by the risk related reasons, when the availability of a berth is limited (reduced), is related to obligatory safety zones around the location of loading/unloading of hazardous cargo from/into a ship: in order to minimize risks, no other operations can be carried out in the safety zones around the place of work (the zone within which the ship is located), and within which the presence of people and resources is strictly limited only to those who are direct participants in the work process.

Calculation of the berths' efficiency scores is based on the real data on the available length of berths by analyzed years—part of the berths which was under maintenance is deducted from the length of berths shown in Table 3.

Water depth, D_w (m)—Water depth is essential for various applications in port management, navigation safety, marine engineering, and environmental monitoring [129,130]. The determination of the water depth is the instrument that, among others, determines the need for dredging [131]. The first step in determining the optimal water depth is to examine the parameters of the hinterland to which a port is gravitating [132]. Data on water depth by berths are given in Table 3.

Operation costs, C_o (EUR)—In the context of an analysis of the risk-related operations costs, it is important to point out that in the structure of total costs—characteristic for functioning of a port—appear a lot of components of costs which are risk related—completely purposed for mitigation of different risk categories. In the available literature, different aspects of the risk management system are referred to as costs, which are summarized in Table 5.

Table 5. An overview of the literature related to costs generated within the risk management system.

The Object of the Research	Reference
To measure the extent to which specific firms have implemented Enterprise Risk Management (ERM) programs.	[133]
To consider a broad range of cyber risk events and actual cost data. To identify cyber losses from an operational risk database and analyze these with appropriate methods.	[134]
To assess indirect natural disaster losses and to analyze their drivers.	[135]
A risk and cost evaluation methodology that can be applied to the analysis of port climate change adaptation measures in situations where data uncertainty is high.	[136]
To estimate the emission costs of ships and trucks in a port, focusing mainly on particular matter and volatile organic compounds.	[137]
The various economic approaches to risk management and cost control in shipping are reviewed.	[138]
The issues of risk-based models and procedural costs in the context of maritime and port security.	[139]

Table 5. Cont.

The Object of the Research	Reference
A review of the costs associated with trade and customs procedures at seaports (trade and customs compliance costs).	[140]
To develop an approach for estimating the economic losses of port disruptions induced by extreme wind events.	[141]
To quantitatively measure the impact of a port-related threat on supply chains and thus highlight the importance of port-related supply chain disruption management.	[142]
Developing Work Breakdown Structure (WBS) standardization on port projects and identifying risks that may occur during project implementation, and considering them in the cost estimation process.	[143]
A conceptual model that ports can follow to ensure that efficient security investment decisions are made to reduce the exposure to terrorist and other unlawful activities.	[144]
To identify the Impact Pathway Approach (IPA) as the best-practice bottom-up methodology for calculating site-specific external costs derived from shipping air emissions.	[145]
Addressing situations in which the decision space of risk management is large and combinatorial, engaging the decision-maker in the allocation of resources to the security, robustness, and resilience of critical infrastructures.	[146]
Internalization of external costs related to air pollution in the ports.	[147]
A general methodology for including <i>risk analysis</i> in an economic–financial analytical model of a port investment project.	[148]

(source: authors).

Values of the operation costs used as an input parameter for calculating efficiency scores by berths take into account the following components:

- daily wages, C_{01-1} (EUR) of workers directly engaged in the cargo handling operation;
- port machinery costs, C_{01-2} (EUR) used in the cargo handling process: depending on the type of the cargo handling operation and type of the cargo, this component of costs is a sum of following items (related to the used types of the port machinery): fuel costs, electric power costs, depreciation costs, and cost of periodical inspection by authorized external body (fulfillment of safety requirements);
- costs of personal safety equipment, C_{01-3} (EUR) of workers directly engaged in the cargo handling process;
- costs of fire truck, C_{01-4} (EUR) used for preventive purposes in the handling operation with liquid bulk cargoes (oil derivatives);
- costs of insurance of workers directly engaged in the cargo handling process, C_{01-5} (EUR);
- costs of using a protective dam, C_{01-6} (EUR), against spills of oil derivatives during handling operations.

It is obvious that some of the previously mentioned components of costs are risk-related and are generated by the implemented risk mitigation measures.

Output: annual cargo throughput by berths (DMU_s), Q_{bi} (t).

Cargo throughput—The factors of influence on the throughput by berths at a port terminal are numerous [149–151] and include characteristics of the berths (length, water depth, . . .), available equipment at the berths (port machinery, . . .), types of cargo handling operations, types of loaded/unloaded cargo, the overall organization and management of the loading/unloading process, the relationship between time required by a cargo ship arriving at the port and the operational capacity of handling equipment at the port [152], hinterland's GDP growth, variables from the group of port performance indicators: ship calls, berthing time, yard occupancy ratio, crane productivity, and ship productivity [151],

the non-containerized throughput shows a strong relation to the national GDP and the volume of national export trade is the key influencing macroeconomic variable to the containerized throughput [150], total foreign import–export trade, the proportion of primary industry and tertiary industry in GDP, and volume of rail cargo turnover [153], etc.

An adequate approach to increase the throughput enables a full use of the potential of a berth (a port terminal/a port) and to identify possibilities for its development [154]. Throughput forecasting is an essential issue in port planning and in ensuring efficient seaport management [149,155] and can be performed using different forecasting models: a multivariate forecasting model to predict port cargo throughput movement at a national level considering macroeconomic indicators [156], by employing business forecasting software, what showed that the robust hybrid strategy achieves accurate predictions of port throughputs against market disruptions [155], a forecasting method based on ship turnaround time, vessel draft, container dwell time, berth productivity, container storage capacity, and custom declaration time [157]. The cargo throughput impacts key port performances [158].

4.1.3. Analyzed Period

Period taken into consideration: 2021–2024.

4.1.4. Data Series

In Table 6, the data series for selected DMUs (berths at the terminal for dry bulk and liquid bulk cargo in the Port of Bar JSC) and selected input and output variables by the years within the analyzed period (from the year 2021 to the year 2024) are presented. As mentioned before, sources of data were official reports from the Port of Bar JSC Information System [106].

Table 6. Data series.

DMU _i	Year	Output		Inputs		
		Annual Throughput (t) ($\times 10^3$)	Number of Directly Engaged Workers ($\times 10^3$)	Berth Length (m) ($\times 10^3$)	Water Depth (m) ($\times 10^3$)	Direct Operation Costs (EUR) ($\times 10^3$)
Berth 01	2021	156.74	0.49	0.185	0.014	34.31
	2022	182.68	0.58	0.185	0.014	39.98
	2023	343.07	1.08	0.185	0.014	75.09
	2024	306.1	0.97	0.185	0.014	67
Berth 02	2021	662.58	1.08	0.185	0.014	175.68
	2022	1084.76	1.76	0.145	0.014	287.62
	2023	323.6	0.53	0.145	0.014	85.8
	2024	204.59	0.33	0.185	0.014	54.25
Berth 03	2021	78.19	0.25	0.06	0.014	34.57
	2022	663.76	2.15	0.185	0.014	293.47
	2023	816.16	2.64	0.185	0.014	360.86
	2024	527.5	1.71	0.155	0.014	233.23
Berth 04	2021	126.7	0.09	0.093	0.006	3.61
	2022	123.48	0.09	0.093	0.006	3.52
	2023	138.17	0.1	0.093	0.006	3.94
	2024	105.61	0.08	0.093	0.006	3.01
Berth 05	2021	30.06	0.02	0.093	0.007	0.77
	2022	2.22	0.002	0.093	0.007	0.057
	2023	1.1	0.001	0.093	0.007	0.028
	2024	0	0	0.093	0.007	0
Berth 06	2021	176.6	0.1	0.093	0.009	10.05
	2022	169.71	0.09	0.093	0.009	9.66
	2023	214.05	0.12	0.093	0.009	12.18
	2024	188.44	0.1	0.093	0.009	10.72

Table 6. Cont.

DMU _i	Year	Output		Inputs		
		Annual Throughput (t) ($\times 10^3$)	Number of Directly Engaged Workers ($\times 10^3$)	Berth Length (m) ($\times 10^3$)	Water Depth (m) ($\times 10^3$)	Direct Operation Costs (EUR) ($\times 10^3$)
Berth 07	2021	50.47	0.027	0.198	0.013	2.87
	2022	83.11	0.045	0.198	0.013	4.73
	2023	30.32	0.016	0.198	0.013	1.73
	2024	20.14	0.011	0.198	0.013	1.15

(source: authors based on [106]). Remark: Values in the previous table are given in thousands of units.

Respecting the objective of the research, whose results are presented in this paper, the values of input and output parameters are related to the whole year. It would be relevant for the next phase of the authors' research to expand the analyses and consider the monthly values of parameters, which could enable recognition of the influence of seasonal variations of parameters (throughput, number of engaged workers, direct operation costs, etc.).

4.2. AHP (Analytic Hierarchy Process) Method

The AHP method is widely used for different purposes. Numerous references are available, where results based on the application of the AHP method are shown, including those related to various aspects of the port management: selection of a port as a node of the supply chain [159], level of a port competitiveness [160], selection of the port machinery as a part of the investment process in a port [161], etc.

The AHP enables solving complex problems at different hierarchical levels, where the goal is at the top, the middle levels are criteria and sub-criteria, and the lowest level is alternatives (choice) [162]. In general, the AHP is used for both discrete and continuous paired comparisons [163], finding the widest applications in multi-criteria decision-making, planning, and resource allocation [164].

The principal steps in implementing the AHP method for defining the intensity of impact of selected risk categories on berths' efficiency in a port (the Port of Bar) are as follows (based on [164,165]):

(A) Defining the goal

The goal is to define the intensity of impact of selected risk categories on berths' efficiency in a port, thus enabling the definition of appropriate risk mitigation measures, optimal utilization of a port's resources through an increased level of operative planning adequacy, and general improvements of berths' performances.

(B) Defining selection criteria and variants (alternatives)

In order to establish bases for defining the intensity of impact of different risk categories on berths' efficiency, using the AHP method, the following selection/comparison criteria are chosen (the same parameters were used as inputs for calculating berths' efficiency scores):

- criterion 1—C1: number of engaged workers;
- criterion 2—C2: berth length;
- criterion 3—C3: water depth;
- criterion 4—C4: operation costs.

Chosen selection/comparison criteria enable establishing an explicit link between the goal of the analysis and some of the basic characteristics of the terminal (port)—berths' length and water depth by berths—where the data collection was performed.

Variants (alternatives)—risks categories whose impact on berths' efficiency is to be considered as follows. Alternatives are chosen based on the process logic, and priority is

given to the risk categories directly generated in the cargo loading/unloading process at the analyzed berths:

Variant (alternative) 1, R1—operational risks—impact on berths' efficiency;

Variant (alternative) 2, R2—technical risks—impact on berths' efficiency;

Variant (alternative) 3, R3—safety risks—impact on berths' efficiency;

Variant (alternative) 4, R4—environmental risks—impact on berths' efficiency.

It is relevant to mention that the selection of these risk categories does not reduce the importance of other important risk categories: cyber risks, . . .

Description of risk categories on which the variants (alternatives) are based is given in Table 7.

Table 7. Description of risk categories.

Risk Category	Description
Operational risks	Lack of management supervision, errors, poor internal controls; the risks generated during the operational planning process, loading/unloading and storage of cargo, . . . [36]; the risk of loss arising from the failure or inadequacy of internal processes, poor work culture, etc. [48].
Technical risks	In adequate maintenance policies caused by the absence of preventive and corrective maintenance, lack of qualified maintenance personnel, lack of adequate stocks of spare parts, insufficient standardization of equipment types, . . . [18].
Safety risks	Poor health and safety procedures; port safety is affected by multiple factors related to design, installation, operation, and maintenance [47]; there are five key factors that influence the effects of potential health hazards [53]: type of health hazard, time period of exposure, level of exposure (dose), mode of exposure (e.g., contact, inhalation, or ingestion), individual susceptibility, etc. Domains of people safety risks: port workers, customers, service providers, ship's crew, . . . [18].
Environmental risks	Resilience is widely seen as a desirable system property in mitigating environmental risks [52]; ship emissions, dredging, oils spills, chemical contaminants, ballast waters, noise pollution, alien species, . . . [27]; the port environment is endangered by ports' hinterland, ports' activities and operations, and ships activities; ports pollution may also result from ship accidents, accidents in ports, land activities, ship bunkering, noises, garbage, dust, dredging, port maintenance, ship air pollution, traffic congestion, sewage etc. [18].

(C) Defining the hierarchical analysis model

The general form of the hierarchical analysis model is shown in Figure 2.

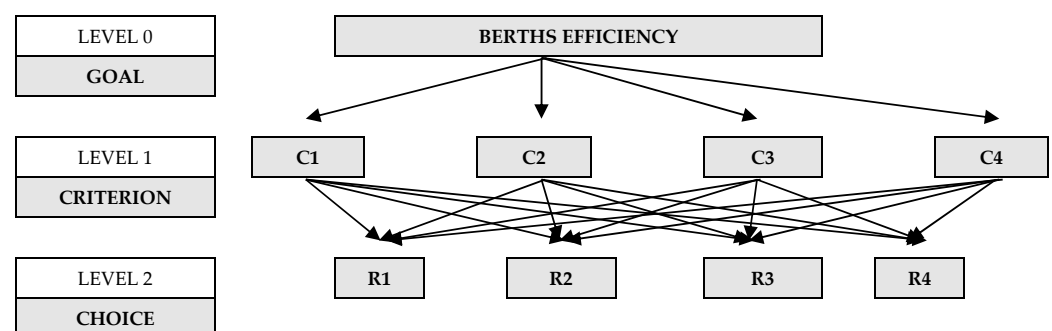


Figure 2. General form of the hierarchy model of analysis (source: authors).

(D) Pair-wise comparison and consistency test

Pair-wise comparisons and related consistency tests are performed through the following activities [165]:

- creating a reciprocal (comparative) matrix (using Saati's fundamental scale of absolute numbers);
- summing each column of the reciprocal (comparison) matrix;
- obtaining the normalized relative weights;
- calculating principal eigen value $\lambda_{\max}$ —the summation of the products between each element of the eigen vector and the sum of columns of the reciprocal (comparison) matrix);
- calculating Consistency Index, CI—a measure of deviation or degree of consistency using the following equation: $CI = (\lambda_{\max} - n)/(n - 1)$, where $\lambda_{\max}$ —principal eigen value; n —number of items for comparison;
- calculating Consistency Ratio, CR—based on the values of Consistency Index, CI, and Random Consistency Index, RI (table values), according to the number of items to be compared, n ; for the analyzed case, $n = 4 \Rightarrow RI = 0.9$; if the value of CR is under 0,10, then the made evaluation is consistent.

(E) Calculate the global weights

The overall composite weight for the analyzed variants (alternatives)—domains of risks, M_i , is calculated based on the following relation:

$$M_i = \Sigma(\text{relative weight of the criterion } c_j, \text{ from the compar. matrix with respect to the goal}) \times (\text{relative weight of the variant (alternat.)—domain of risks } M_i \text{ based on criterion } c_j, \text{ from compar. matrix with respect to criterion } c_j) \quad (10)$$

(F) Final ranking of alternatives.

5. Results

5.1. Efficiency Scores for Defined DMU_s (Berths)

Based on the values of input and output variables given in Table 6, efficiency scores for defined DMUs (berths), per year from the analyzed period (2021 to 2024), are calculated using appropriate software (based on the DEA CCR input-oriented model) and given in Table 8.

Efficiency scores are graphically presented in Figure 3.

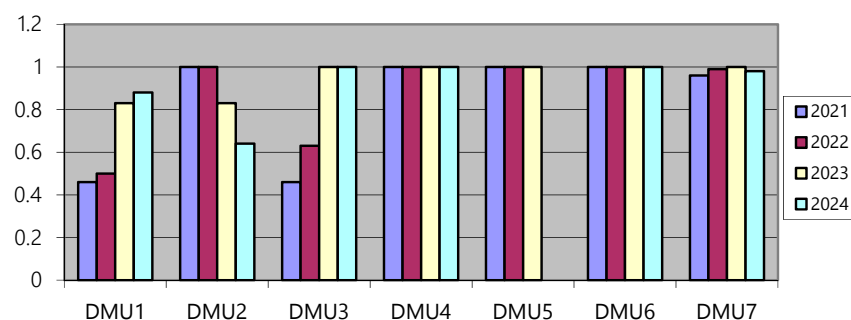


Figure 3. Efficiency scores (source: authors).

Table 8. Efficiency scores.

DMU _i , Berths	2021		2022		2023		2024	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
01	0.4632	6	0.5019	7	0.8291	7	0.8806	5
02	1	1	1	1	0.8309	6	0.6405	6
03	0.4597	7	0.6119	6	1	1	1	1

Table 8. Cont.

DMU _i , Berths	2021		2022		2023		2024	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
04	1	1	1	1	1	1	1	1
05	1	1	1	1	1	1	0	7
06	1	1	1	1	1	1	1	1
07	0.9638	5	0.9882	5	1	1	0.9828	4

(source: authors).

5.2. Intensity of Impact of Risks on Berths' Efficiency

5.2.1. Pair-Wise Comparisons and Consistency Tests—Level 1 and Level 2 of the Hierarchy Framework

In line with the steps described in Section 4.2, reciprocal matrices were calculated for all related parameters, and consistency tests were performed, having as an initial objective establishing bases for defining the intensity of the impact of risk categories explained in Table 7 on berths' efficiency. Pair-wise comparisons are carried out by an ad hoc working group consisting of the authors of this paper (four persons) and port professionals—from the Port of Bar (eight persons). In the matrices are inserted mean values (rounded values) of ratings from all involved persons. Although the ratings still have a component of subjectivity, this increased number of involved professionals from the domain of risk management reduces the impact of isolated individual opinions on the scores. Results are systematized in Table 9.

Table 9. Reciprocal matrices, characteristic parameters, and consistency tests.

Reciprocal Matrices						Characteristic Parameters and Consistency Tests
Level 1 of the hierarchy framework—goal						
Criterion	C1	C2	C3	C4	Priority Vector	Principal Eigen vector: $\lambda_{\max} = 4.1427$; Consistency Index, CI = 0.0476; Random value of consistency index, RI = 0.9; Consistency ratio, CR = 0.0528; Consistency ratio is under 0.10, which means that the performed evaluation is consistent.
C1	1.00	3.00	3.00	0.50	0.3095	
C2	0.33	1.00	2.00	0.33	0.1496	
C3	0.33	0.50	1.00	0.33	0.1052	
C4	2.00	3.00	3.00	1.00	0.4357	
sum	3.66	7.50	9.00	2.16	1.0000	
Level 2 of the hierarchy framework—criterion 1						
Criterion	R1	R2	R3	R4	Priority Vector	Principal Eigen vector: $\lambda_{\max} = 4.2437$; Consistency Index, CI = 0.0812; Random value of consistency index, RI = 0.9; Consistency ratio, CR = 0.0903; Consistency ratio is under 0.10, which means that the performed evaluation is consistent.
R1	1.00	2.00	0.33	2.00	0.2260	
R2	0.50	1.00	0.33	3.00	0.1893	
R3	3.00	3.00	1.00	3.00	0.4774	
R4	0.50	0.33	0.33	1.00	0.1073	
sum	5.00	6.33	1.99	9.00	1.0000	
Level 2 of the hierarchy framework—criterion 2						
Criterion	R1	R2	R3	R4	Priority Vector	Principal Eigen vector: $\lambda_{\max} = 4.2515$; Consistency Index, CI = 0.0838; Random value of consistency index, RI = 0.9; Consistency ratio, CR = 0.0932; Consistency ratio is under 0.10, which means that the performed evaluation is consistent.
R1	1.00	3.00	2.00	2.00	0.4196	
R2	0.33	1.00	2.00	2.00	0.2477	
R3	0.50	0.50	1.00	2.00	0.1955	
R4	0.50	0.50	0.50	1.00	0.1371	
sum	2.33	5.00	5.50	7.00	1.0000	

Table 9. Cont.

Reciprocal Matrices						Characteristic Parameters and Consistency Tests
Level 2 of the hierarchy framework—criterion 3						
Criterion	R1	R2	R3	R4	Priority Vector	Principal Eigen vector: $\lambda_{\max} = 4.1353$; Consistency Index, CI = 0.0451; Random value of consistency index, RI = 0.9; Consistency ratio, CR = 0.0501; Consistency ratio is under 0.10, which means that the performed evaluation is consistent.
R1	1.00	0.50	2.00	2.00	0.2748	
R2	2.00	1.00	2.00	2.00	0.3873	
R3	0.50	0.50	1.00	0.50	0.1397	
R4	0.50	0.50	2.00	1.00	0.1981	
sum	4.00	2.50	7.00	5.50	1.0000	
Level 2 of the hierarchy framework—criterion 4						
Criterion	R1	R2	R3	R4	Priority Vector	Principal Eigen vector: $\lambda_{\max} = 4.2383$; Consistency Index, CI = 0.0794; Random value of consistency index, RI = 0.9; Consistency ratio, CR = 0.0883; Consistency ratio is under 0.10, which means that the performed evaluation is consistent.
R1	1.00	3.00	2.00	3.00	0.4429	
R2	0.33	1.00	2.00	2.00	0.2376	
R3	0.50	0.50	1.00	3.00	0.2131	
R4	0.33	0.50	0.33	1.00	0.1065	
sum	2.16	5.00	5.33	9.00	1.0000	

(source: authors).

5.2.2. Overall Composite Weights (Synthesizing Results) and Final Ranking

The overall composite weight of each variant (alternative)—intensity of impact of risk categories on berths' efficiency—is calculated using Equation (10) and values of parameters from Table 9. It is the normalization of the linear combination of multiplication between weight and priority Eigen Vectors (Priority Vectors). Overall composite weight for variants (alternatives) is as follows:

$$\mathbf{R1} = (0.3095 \times 0.2260) + (0.1496 \times 0.4196) + (0.1052 \times 0.2748) + (0.4357 \times 0.4429) = 0.3546$$

$$\mathbf{R2} = (0.3095 \times 0.1893) + (0.1496 \times 0.2477) + (0.1052 \times 0.3873) + (0.4357 \times 0.2376) = 0.2399$$

$$\mathbf{R3} = (0.3095 \times 0.4774) + (0.1496 \times 0.1955) + (0.1052 \times 0.1397) + (0.4357 \times 0.2131) = 0.2845$$

$$\mathbf{R4} = (0.3095 \times 0.1073) + (0.1496 \times 0.1371) + (0.1052 \times 0.1981) + (0.4357 \times 0.1065) = 0.1209$$

Overall composite weight of the analyzed variants (alternatives) is presented with the following matrix—Table 10.

Table 10. Values of composite weights.

	C1	C2	C3	C4	Composite Weight
R1	0.2260	0.4196	0.2748	0.4429	0.3546
R2	0.1893	0.2477	0.3873	0.2376	0.2399
R3	0.4774	0.1955	0.1397	0.2131	0.2845
R4	0.1073	0.1371	0.1981	0.1065	0.1209
	1.0000	1.0000	1.0000	1.0000	1.0000

(source: authors).

Overall consistency of the hierarchy, CR, is 0.0769 (under 0.10), which means that the complete evaluation (at level 1 and level 2) is consistent.

6. Discussion

Berth 04 (DMU₄), purposed for unloading operations with dry bulk cargo and Berth 06 (DMU₆), purposed for loading/unloading operations with liquid bulk cargo in all

years from the analyzed period had the highest efficiency scores—were the most efficient (average rank per year for both berths was “1”).

The efficiency of all other berths has varied per year during the analyzed period. The average efficiency rank of Berth 01 (DMU₁) for the period was “6”. The efficiency of this berth showed an increasing trend over the period: scores have grown from the value 0.4632 (2021) to 0.08806 (2024). The trend of the efficiency score was in line with the trend of the output (throughput) parameter value for the first three years of the period. As quay length and water depth were constant over the period, obviously, variation in the efficiency scores was caused by changing values of the number of workers directly engaged in the handling operations with cargo and direct operation costs.

The average efficiency rank of Berth 02 (DMU₂) for the period was “4”. In the first two years of the period, the efficiency of this berth was at the highest level (“1”), and in the last two years of the period, the efficiency had a decreasing trend (2023—0.8309; 2024—0.6405). Efficiency scores are in line with the trend of output values. Variations in the level of efficiency of this berth were caused by variations in values of three out of four inputs—only water depth did not change throughout the analyzed period.

On average, the efficiency rank of Berth 03 (DMU₃) was “4”. Efficiency scores had an increasing trend. From the value 0.4597 in the first year of the analyzed period, the efficiency score reached the highest level (“1”) in the third year, and it was kept in the fourth year, too. As one of the inputs (water depth) was constant throughout the period, variations in the efficiency scores were caused by changes in the values of the remaining three inputs over the years of the period. In the first three years of the period, the trend of the efficiency score was in line with the trend of values of the output. Although the output was reduced in the fourth year, the efficiency score remained at the highest level (“1”).

The average efficiency rank of Berth 05 (DMU₅) was “3”, which was determined by the fact that there was no throughput on this berth in 2024. In the first three years of the period, the efficiency score was “1”, although the throughput (output) was at a very low level. It was reached on the basis of a favorable relation between the values of output (throughput) and used inputs.

The average efficiency rank of Berth 07 (DMU₇) was “4”. Efficiency scores varied throughout the analyzed period and took different values per year. In the first three years, the efficiency score had an increasing trend from 0.9638 (in 2021) to 1 (in 2023). The value of the efficiency decreased in 2024 to a value of 0.9828. In the first two years, as well as in the fourth year of the analyzed period, the trend of efficiency scores was in line with the changes in output values. Bearing in mind that two inputs (berth length and water depth) were constant throughout the period, variations of efficiency scores were mainly caused by changes in values of the remaining two inputs (number of directly engaged workers and operation costs).

If the trends of efficiency scores (Table 8 and Figure 3) and related values of output and inputs parameters, by intervals of the analyzed period, are taken into consideration, then cases of “imbalance” can be identified: trends of the efficiency scores and output and inputs values are not in line, as presented in Table 11.

Table 11. A comparison of trends: efficiency scores vs. values of output and inputs.

DMU _i -berths	Parameter	Trends by Intervals (Values of Output and Inputs ×10 ³)								
		2021–2022		2022–2023		2023–2024				
01	Efficiency score	0.4632	+	0.5019	0.5019	+	0.8291	0.8291	+	0.8806
	Output—Throughput	156.74	+	182.68	182.68	+	343.07	343.07	-	306.10
	Input 1—Workers	0.49	+	0.58	0.58	+	1.08	1.08	-	0.97
	Input 2—Berth length	0.185	=	0.185	0.185	=	0.185	0.185	=	0.185
	Input 3—Water depth	0.014	=	0.014	0.014	=	0.014	0.014	=	0.014
	Input 4—Direct costs	34.31	+	39.98	39.98	+	75.09	75.09	-	67

Table 11. Cont.

DMU _i -berths	Parameter	Trends by Intervals (Values of Output and Inputs ×10 ³)								
		2021–2022			2022–2023			2023–2024		
02	Efficiency score	1	=	1	1	-	0.8309	0.8309	-	0.6405
	Output—Throughput	662.58	+	1084.76	1084.76	-	323.60	323.60	-	204.59
	Input 1—Workers	1.08	+	1.76	1.76	-	0.53	0.53	-	0.33
	Input 2—Berth length	0.185	-	0.145	0.145	=	0.145	0.145	+	0.185
	Input 3—Water depth	0.014	=	0.014	0.014	=	0.014	0.014	=	0.104
	Input 4—Direct costs	175.68	+	287.62	287.62	-	85.80	85.80	-	54.25
03	Efficiency score	0.4597	+	0.6119	0.6119	+	1	1	=	1
	Output—Throughput	78.19	+	663.79	663.79	+	816.16	816.16	-	527.50
	Input 1—Workers	0.25	+	2.15	2.15	+	2.64	2.64	-	1.71
	Input 2—Berth length	0.060	+	0.185	0.185	=	0.185	0.185	-	0.155
	Input 3—Water depth	0.014	=	0.014	0.014	=	0.014	0.014	=	0.014
	Input 4—Direct costs	34.57	+	295.47	295.47	+	360.86	360.86	-	233.23
04	Efficiency score	1	=	1	1	=	1	1	=	1
	Output—Throughput	126.70	-	123.48	123.48	+	138.17	138.17	-	105.61
	Input 1—Workers	0.09	=	0.09	0.09	+	0.10	0.10	-	0.08
	Input 2—Berth length	0.093	=	0.093	0.093	=	0.093	0.093	=	0.093
	Input 3—Water depth	0.006	=	0.006	0.006	=	0.006	0.006	=	0.006
	Input 4—Direct costs	3.61	-	3.52	3.52	+	3.94	3.94	-	3.01
05	Efficiency score	1	=	1	1	=	1	1	-	0
	Output—Throughput	30.06	-	2.22	2.22	-	1.10	1.10	-	0
	Input 1—Workers	0.02	-	0.002	0.002	-	0.001	0.001	-	0
	Input 2—Berth length	0.093	=	0.093	0.093	=	0.093	0.093	=	0.093
	Input 3—Water depth	0.007	=	0.007	0.007	=	0.007	0.007	=	0.007
	Input 4—Direct costs	0.77	-	0.057	0.057	-	0.028	0.028	-	0
06	Efficiency score	1	=	1	1	=	1	1	=	1
	Output—Throughput	176.6	-	169.71	169.71	+	214.05	214.05	-	188.44
	Input 1—Workers	0.1	-	0.09	0.09	+	0.12	0.12	-	0.1
	Input 2—Berth length	0.093	=	0.093	0.093	=	0.093	0.093	=	0.093
	Input 3—Water depth	0.009	=	0.009	0.009	=	0.009	0.009	=	0.009
	Input 4—Direct costs	10.05	-	9.66	9.66	+	12.18	12.18	-	10.72
07	Efficiency score	0.9638	+	0.9882	0.9882	+	1	1	-	0.9828
	Output—Throughput	50.47	+	83.11	83.11	-	30.32	30.32	-	20.14
	Input 1—Workers	0.027	+	0.043	0.043	-	0.016	0.016	-	0.011
	Input 2—Berth length	0.198	=	0.198	0.198	=	0.198	0.198	=	0.198
	Input 3—Water depth	0.013	=	0.013	0.013	=	0.013	0.013	=	0.013
	Input 4—Direct costs	2.87	+	4.73	4.73	-	1.73	1.73	-	1.15

(source: authors). Symbols used in Table 11: “+”—increasing trend; “-”—decreasing trend; “=”—no changes of values; —Trends are not balanced.

Results of the analyses given in Table 11 indicate the existence of complex correlations between the efficiency scores and values of output/input parameters, which are to be examined in the next phase of the authors’ research.

In order to establish a base for conclusions about the impact of risks on the berth efficiency, it is important to recognize that all inputs used for calculation of the efficiency scores have a “risk-related component”—a part of the value which is completely determined by the risk mitigation measure—related to resources purposed only for mitigating risks. Those “risk-related components”, mentioned in Section 4.1.2 of this paper, can be considered as unavoidable and enable the reduction or elimination of related risks.

In this context, two relevant indicators of the general importance of the risk management in a port can be identified: the significant percentage of the risk-related workers who participate in the realization of loading/unloading operations with cargo (with full working time dedicated to actions from the domain of risk management) and the high share of risk-related costs in total operational costs, especially for loading/unloading operations with cargo, is noteworthy. It becomes clear that risk management inevitably requires the engagement of resources that provide a “platform” (a basis) for further activities directed to optimizing the efficiency in a port—an optimization of the relationship between used inputs to obtain desired outputs. In that sense, it is necessary to continuously review the adequacy of the functioning of the risk management system in order to identify whether the optimal level of resource allocation in that domain has been reached. One of the initial steps in this direction is to identify and analyze the intensity of impact of different risk categories on berth efficiency.

Based on the analysis performed in Section 5.2, the intensity of impact of different risk categories on berths’ efficiency can be ranked as follows:

- Rank 1: Variant (alternative) 1, R1—operational risks—overall composite weight: 0.3546 (35.46%);
- Rank 2: Variant (alternative) 3, R3—safety risks—overall composite weight share: 0.2845 (28.45%);
- Rank 3: Variant (alternative) 2, R2—technical risks—overall composite weight: 0.2399 (23.99%);
- Rank 4: Variant (alternative) 4, R4—environmental risks—overall composite weight: 0.1209 (12.09%).

Results of the analysis indicate that 63.91% of the impact of risks on berths' efficiency is related to the operational risks and safety risks.

In line with the presented results and in order to fulfill preconditions for optimization of the berths' efficiency, it is necessary to give priority to a very wide set of managerial activities with the objective of creating and implementing optimal risk mitigating (and port resilience strategy):

- related to the Variant (alternative) 1, R1—operational risks: to improve management supervision and internal controls; to improve planning of the cargo handling process (optimization of allocation of resources), to improve parameters of the cargo handling process realization (increasing productivity, minimization/elimination of working process interruptions, . . .); etc.
- related to Variant (alternative) 3, R3—safety risks: to optimize health and safety procedures; to optimize usage of personal protective equipment; to minimize period of exposure and mode of exposure of workers; to carry out, strictly in line with the related regulation, all necessary safety inspections of the port infrastructure, port superstructure, port machinery by the authorized external bodies; to implement the safety management system which involves preventive measures referred on all persons within the port area (port workers, customers, service providers, ship's crew, . . .); etc.
- related to Variant (alternative) 2, R2—technical risks: to optimize the level of qualification of maintenance personnel; to optimize implemented maintenance policies; to optimally carry out preventive and corrective maintenance of all port technical systems, etc.
- related to Variant (alternative) 4, R4—environmental risks: to establish the optimal environmental management system which will prevent negative impacts/different environmental aspects: emissions to air (cargo handling operations, port machinery, ships, open areas, . . .), spillages to water (from ships, from the port territory), spillages to soil; generation of waste; usage of resources (electricity, water); noise pollution; relation with the local community; etc.

Ranks of the Variant (alternative) 1, R1—operational risks, as per the used selection criteria, are as follows:

- according to criterion 1—C1: number of workers engaged in the cargo handling process, has the rank "3", with a weight of 0.2260 (22.60%);
- according to criterion 2—C2: berth length, has the rank "1", with a weight of 0.4196 (41.96%);
- according to criterion 3—C3: water depth, has the rank "2", with a weight of 0.2748 (27.48%);
- according to criterion 4—C4: operation costs, has the rank "1", a weight of 0.4429 (44.29%).

Ranks of the Variant (alternative) 3, R3—safety risks, as per the used selection criteria, are as follows:

- according to criterion 1—C1: number of workers engaged in the cargo handling process, has the rank “1”, with a weight of 0.4774 (47.74%);
- according to criterion 2—C2: berth length, has the rank “3”, with a weight of 0.1955 (19.55%);
- according to criterion 3—C3: water depth, has the rank “4”, with a weight of 0.1394 (13.94%);
- according to criterion 4—C4: operation costs, has the rank “3”, a weight of 0.2131 (21.31%).

Ranks of the Variant (alternative) 2, R2—technical risks, as per the used selection criteria, are as follows:

- according to criterion 1—C1: number of workers engaged in the cargo handling process, has the rank “3”, with a weight of 0.1893 (18.93%);
- according to criterion 2—C2: berth length, has the rank “2”, with a weight of 0.2477 (24.77%);
- according to criterion 3—C3: water depth, has the rank “1”, with a weight of 0.3873 (38.73%);
- according to criterion 4—C4: operation costs, has the rank “2”, a weight of 0.2376 (23.76%).

Ranks of the Variant (alternative) 4, R4—environmental risks, as per the used selection criteria, are as follows:

- according to criterion 1—C1: number of workers engaged in the cargo handling process, has the rank “4”, with a weight of 0.1073 (10.73%);
- according to criterion 2—C2: berth length, has the rank “4”, with a weight of 0.1371 (13.71%);
- according to criterion 3—C3: water depth, has the rank “3”, with a weight of 0.1981 (19.81%);
- according to criterion 4—C4: operation costs, has the rank “4”, with a weight of 0.1065 (10.65%).

Looking from the general point of view, the five highest weights are referred to the following variants (alternatives) and criteria:

- Variant (alternative) 3, R3—safety risks, according to criterion 1—C1: number of workers engaged in the cargo handling process: weight of 0.4774 (47.74%);
- Variant (alternative) 1, R1—operational risks, according to criterion 4—C4: operation costs: weight of 0.4429 (44.29%);
- Variant (alternative) 1, R1—operational risks, according to criterion 2—C2: berth length: weight of 0.4196 (41.96%);
- Variant (alternative) 2, R2—technical risks, according to criterion 3—C3: water depth: weight of 0.3873 (38.73%).

All these results can be used as additional bases for directing activities in both domains: increasing level of berths’ efficiency and optimizing implemented risk mitigation measures, indicating correlations which deserve special attention: safety risks—workers; operational risks—operation costs; operational risks—berth length (availability of berths for receiving ships, . . .); technical risks—water depth (dependence of size of ships which can be received on water depth, . . .).

According to the presented results, the intensity of the influence of certain risk categories on berths’ efficiency can be determined, thereby establishing the basis for improving the process of operational planning, optimizing the level of utilization of port resources, and increasing the level of utilization of the available capacities of a port/terminal (through increased level of utilization of workers, operational quay, port machinery, and through op-

eration costs optimization), as well as for defining adequate risk management models and strategies for achieving maximal resilience of a port to the negative impacts of disruptive factors from the highly changing environment where the port is functioning.

At the same time, the results can serve as a basis for reducing the time the ships stay at the anchorage, but also for improving maritime safety and designing a collision avoidance strategy within the water area of the specific port (or within the wider area).

In the previous context, it is important to state that risks from the domain of maritime safety within the port water area can be classified into two groups: risks related to the navigation of the ship from the anchorage to the berth where the ship is to be berthed (and vice versa) and risks characteristic for the berthing process itself. Bearing in mind that the categorization of the intensity of impact of different risks categories on berth efficiency was also carried out on the basis of the selection criteria “berth length” and “water depth”, which are, at the same time, factors with a decisive influence on maritime safety within the port water area, a basis for determining the character and intensity of the correlation between berths’ efficiency and the parameters that determine maritime safety within the port water area can be identified.

Maritime safety is one of the factors affecting the port construction and its further development [166]. In general, the factors that determine maritime safety (including maritime safety within the port water area) and provide a basis for developing more effective strategies and policies in that domain are human resources competence, berth length, water depth, currents in the port water area, weather conditions, technological risks, ship construction (characteristics: LOA, breadth, draft, . . .), adequacy of its maintenance, port’s capacity for emergency response, etc. [167–170]. Berthing is one of the most risky phases in the process of ship navigation within the port waters, and its risk assessment is crucial for both ship safety and port scheduling [168]. Special attention has to be given to the berthing of hazardous cargo ships [170].

About 90% of maritime accidents occur in restricted regions or in shallow waters, where the effects of wind, sea, and currents on ships become more significant as they are at low speed. These conditions could increase the risk of accidents, such as collisions between ships, between ships and port structures, etc. [171]. The most frequent type of maritime accident in the port is the ship collision [172]. It is the key reason why identifying the distribution pattern and influencing factors of ship collision risk is crucial for ensuring navigation safety, operation, and management efficiency in port waters [173–175]. Ship collision accidents are connected with consequent intensive negative impacts in different domains (people, assets, . . .), and this is particularly related to port basins [176]. Existence of ship collision risks within the port water area prompt the need for robust risk assessment models to enhance safety measures [177], which, among others, include [178] the design of ship traffic separation schemes, the selection and positioning of aids to navigation, and the definition of operational requirements from a ship traffic management perspective. Key factors important for collision avoidance are [179] relative speed, the Distance to the Closest Point of Approach (DCPA), the Closest Point of Approach (TCPA), and the ratio of the lengths of the giving-way and stand-on ships. Collision avoidance traditional methods often rely on collision risk assessments, using quantitative indicators, statistical analysis, or empirical models. As the effectiveness of these methods is limited, some new methods are introduced: a machine learning method, neural networks, fuzzy logic, etc. [176,179–181]. Ship collision avoidance is not only a hot topic in the shipping industry but also an eye-catching issue in the development of intelligent ships [182] and for the safe navigation of unmanned surface vehicles (USVs) [183].

7. Conclusions

Considerations carried out in this paper directly confirm the highest level of importance of risk management in a port whose adequacy degree directly determines capability of a port to answer on its multidimensional role in functioning of the economic system to whom it is gravitating, through transport, production, trade, and other related activities, as well as role in importing/exporting/producing energy.

The variety of risks, their potential negative influence, and necessary continuous preventive and corrective measures, which have to be taken in order to mitigate risks, are—unavoidably—followed by an impact of the risk-related parameters on port efficiency (its different metrics: efficiency of the whole port, efficiency of terminals, efficiency of the berth, . . .), as well as on other port characteristics.

Using a methodology adjusted to the concrete object of analysis, based on a combination of the DEA CCR input-oriented method and the AHP method, after definition of efficiency scores for the analyzed berths, the impact of different risk categories on berths' efficiency was identified. Based on the results of the conducted analysis, it can be said that the most intensive impact on the berths' efficiency had operational risks, rather than safety, technical, and environmental risks.

It is necessary to add that calculated ranks of intensity of risks impact on berths' do not eliminate the importance of other risk classes not included in the analyses (climate risks, cyber risks, . . .) and indicate the necessity of continuous activities in reducing risks/improving efficiency in a port (in different fields: port organization, investing in improvements of cargo handling technologies, . . .).

The proposed approach for identifying, analyzing, and quantifying the influence of different risk categories on berth efficiency in a port can be implemented (replicated) in other ports. It is ensured by including in the analyses the output (throughput), inputs (number of workers, berth length, water depth, direct operation costs), and categories of risks, which are not specific only for the analyzed terminal but common for all ports/terminals. As well, the proposed approach can be implemented for the consideration of efficiency in other systems in the function of risks and risk-related input parameters. Considerations are relevant for establishing bases for optimizing an overall port resilience strategy, including improvements in maritime safety and mitigating ship collision avoidance, too. Considering that studies on direct correlations between the efficiency in ports (terminals) and different categories of risks are not so frequent in the available literature, the authors' intention is to try to contribute with this paper by highlighting some aspects of the mentioned correlations.

The authors plan to continue work in the domain of risk management in ports and correlations between different metrics of the ports' efficiency and relevant risks categories, including maritime safety risks and ship collision risks in the port water area, respecting all key influential factors (patterns of ships arrival on anchorage, depending on the contractual obligations towards port users, distribution of times of ships' berthing and un-berthing, etc.). Through the planned research, influence of types of cargo handled and level of specialization of a port terminal will be taken into consideration for calculating efficiency scores, aiming, in general, to use a wider set of input parameters and to include, in addition to "internal" (characteristic for a port/terminal itself), external inputs (parameters related to the infrastructure which connect a port with the hinterland, . . .). As well, one of the relevant directions of the authors' further engagement is the extension of the research on additional ports from the Adriatic–Ionian region.

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