Merging Multiple System Perspectives

The Key to Effective Inland Shipping Emission-Reduction Policy Design

van der Werff, Solange; Baart, Fedor; van Koningsveld, Mark

DOI
10.3390/jmse13040716

Publication date
2025

Document Version
Final published version

Published in
Journal of Marine Science and Engineering

Citation (APA)
van der Werff, S., Baart, F., & van Koningsveld, M. (2025). Merging Multiple System Perspectives: The Key to Effective Inland Shipping Emission-Reduction Policy Design. *Journal of Marine Science and Engineering*, *13*(4), Article 716. https://doi.org/10.3390/jmse13040716

Journal of
Marine Science and Engineering

Article

Merging Multiple System Perspectives: The Key to Effective Inland Shipping Emission-Reduction Policy Design

Solange van der Werff [1,*], Fedor Baart [2] and Mark van Koningsveld [1,3]

[1] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, P.O. Box 5048, 2628 CN Delft, The Netherlands; m.vankoningsveld@tudelft.nl
[2] Rijkswaterstaat, P.O. Box 2232, 3500 GE Utrecht, The Netherlands
[3] Van Oord Dredging and Marine Contractors B.V., Schaardijk 211, P.O. Box 8574, 3063 NH Rotterdam, The Netherlands
* Correspondence: s.e.vanderwerff@tudelft.nl

Abstract: Policymakers in the maritime sector face the challenge of designing and implementing decarbonization policies while maintaining safe navigation. Herein, the inland sector serves as a promising stepping stone due to the possibility of creating a dense energy supply infrastructure and shorter distances compared to marine shipping. A key challenge is to consider the totality of all operational profiles as a result of the range of vessels and routes encountering varying local circumstances. In this study, we use a new scheme called "event table" to transform big data on vessel trajectories (AIS data) combined with energy-estimating algorithms into shipping-emission outcomes that can be evaluated from multiple perspectives. We can subsequently tie observations in one perspective (for example, large-scale spatial patterns on a map) to supporting explanations based on another perspective (for example, water currents, vessel speeds, or engine ages and their contributions to emissions). Hence, combining these outcomes from multiple perspectives and evaluation scales provides an essential understanding of how the system works and what the most effective improvement measures will be. With our approach, we can translate large quantities of data from multiple sources into multiple linked perspectives on the shipping system.

Keywords: shipping emissions; AIS data; inland shipping; event table

Academic Editor: Theocharis D. Tsoutsos

Received: 4 March 2025
Revised: 24 March 2025
Accepted: 31 March 2025
Published: 3 April 2025

Citation: van der Werff, S.; Baart, F.; van Koningsveld, M. Merging Multiple System Perspectives: The Key to Effective Inland Shipping Emission-Reduction Policy Design. *J. Mar. Sci. Eng.* **2025**, *13*, 716. https://doi.org/10.3390/jmse13040716

1. Introduction

Worldwide, multiple economic sectors face ambitious emission reduction targets following the Paris Climate Agreement [1]. The European Green Deal [2] states that the inland shipping industry should contribute to these targets in two ways: as an alternative for less clean transport modes (emission reduction through modal shift) and by reducing the emissions of maritime transport itself (shipping emissions reduction). The modal-shift-related reduction follows from inland shipping being considered relatively environmentally friendly, with CO_2 emissions per ton-kilometers a factor of six lower than for road transport, and contributing to decongesting road networks [2]. Concerning the reduction in shipping emissions, an ambition to decrease shipping emissions by 50% in 2050 was set by the International Maritime Organisation (IMO) [3]. The Dutch inland shipping sector set its own ambitions to reduce greenhouse gas emissions by 55% in 2030 and to become climate-neutral in 2050 in the Dutch Inland Shipping Green Deal [4]. Policy makers now face the challenge of determining what (package of) measures they should implement to achieve the desired improvements.

We can identify three interrelated challenges when designing policies for the inland shipping sector. First, there is a large diversity of solutions that can be developed and implemented, ranging from highly targeted to very broad, with different effects locally and on the large scale. Second, the characteristics of fairways vary between corridors and even between fairway segments locally, resulting in different operating conditions for the inland vessels running on them. Third, the inland shipping sector constitutes a large share of the spot market, which makes vessel routing unpredictable. The first challenge can be considered based on Table 1, indicating regulatory, subsidy and operational examples of emission-reduction measures. Measures can be globally applicable, basically addressing all vessels anywhere, regardless of their type or size, or targeted, considering specific vessels [5], specific areas (locks or port areas) or corridors [6], or a combination of them [7]. To understand which measures are effective and at what scale and scope they should be implemented requires an evaluation that is detailed enough to consider the impact of local measures on the one hand and covering a sufficiently large scope on the other.

Table 1. Examples of various emission-reduction measure types (RED is the Renewable Energy Directive and ETS is the Emissions Trading System).

	Global	**Targeted**
Regulations	Fuel composition (EU regulations RED-III and ETS-2)	Local air quality requirements (municipalities, port authorities)
Subsidies	Engine renewal (compliant with latest emission standards)	Zero-emission shipping concepts, Alternative fuel corridors
Operational	Speed limits, water management implementation	Optimizing lock operations, providing shore power

The second challenge considers the large influence of environmental conditions on the emissions and their spatial and temporal variations. Luo et al. [8] demonstrated the necessity of considering dynamic meteorological conditions in vessel sailing speed optimization models as opposed to static predictions. This importance also comes forward in literature on measurement campaigns executed at the banks of busy shipping routes like the Yangtze river [9], the Rhine river [10–12] and the Waal river [13]. All studies emphasize the strictly limited applicability of the results to the measurement location due to the large influence of environmental conditions on the measured emissions and their spatial variations. Jiang et al. [9] compared Automatic Identification System (AIS)-based calculation with measurements and found large differences that could partially be assigned to the effect of environmental conditions, which were not considered in the calculation model. Eger et al. [11] conclude based on their data that vessels adjust their behavior according to the encountered current, whereby upstream sailing vessels use a slightly higher engine load setting and thereby have a slightly higher Speed Through Water (STW); the environmental conditions influence the emission levels directly as well as indirectly through the adapted behavior of the vessel. Keuken et al. [13], furthermore, concluded that one out of three vessels is a 'gross' polluter, implying that a focused targeting of the most polluting ships could be an effective way to reduce a large share of the emissions. Considering variations in vessel and operational characteristics as well as environmental conditions, PIANC-InCom-WG234 [14] concluded that different corridors have different decarbonization paths, calling for an approach that can consider the contributions of local influences to large-scale emission estimates.

Finally, the unpredictability of inland vessel routing is a challenge because of the uncertainty it introduces when extrapolating case-study results to region-level or fleet-level conclusions. Life-cycle analyses have been made to derive potential emission reductions for alternative energy sources like methanol, Liquefied Natural Gas (LNG), hydrogen or batteries [15–17], or for scrubbers [18], and speed optimization studies were conducted for various propulsion systems [19,20]. Furthermore, energy supply solutions have been addressed for port areas [21] and for inland waters [22]. Many of these studies focused their analyses on one or a small number of representative ship-environment combinations described by several case design parameters. Given that the operational profile of a vessel varies greatly, a feasible solution for a case defined by these specific parameters might not be feasible in reality. For example, Tan et al. [18] recommended integrating their approach in a shipping network, incorporating various ship sizes, and to "investigate the choice behaviors of ships". Šimenc [23] concluded, based on a comparison of emission calculators, that the outcomes of various methods vary depending on different parameters that may be applicable at region level, to ship level, and even up to "waterway sections of a single transport operation by the same ship". Hence, the case studies should be evaluated in a broader context. To conduct this, a better understanding of the operational profiles of vessels, as well as the role of the encountered environmental conditions, is required.

Following the three challenges and what is required to tackle each of them, the goal in this article is to evaluate emissions considering the interconnectivity between processes and influences at the detail level on one hand and the emission patterns at the large-scale level. For maritime applications, the first steps have been made by linking large-scale emission patterns derived based on AIS tracks, often presented in heat maps, to characteristics at the ship level. Goldsworthy and Goldsworthy [24] indicated the contributions of distinguished operational modes to the total shipping emissions of sea-going vessels, and Jalkanen et al. [25] made a breakdown of the total maritime shipping emissions into vessel size categories. As reflected by the three challenges, inland shipping emissions and the feasibility of potential policy measures are strongly affected by spatially varying conditions. This drives the desire to further expand the possibilities to identify underlying details, from just ship-related details to details that are related to location or time, or both. Commonly used system representations, or "schemes" for evaluating systems, do not accommodate investigating each of these details at once. Therefore, we apply a new, multi-perspective enabled scheme, called an "event table", that facilitates deriving an overview of large-scale patterns, as well as inspecting the detailed contributions of processes related to vessel characteristics as well as environmental conditions in time and space.

We aim to demonstrate that these various perspectives and evaluation scales help identify the most promising targeted emission reduction measures, like the examples stated in Table 1. We conduct this by considering the case study of vessel emissions on the Dutch inland water transport network. The presented results go beyond a presentation of the emission patterns and dive deeper into their root causes to finally help answer questions like "how can we design a strategy for fleet electrification?" and "how much will engine replacement contribute to emission reduction in this system?" The applied scheme, presented in Section 2.3, facilitates joining multiple data sources and calculation approaches that are first introduced in Section 2. The event table offers the flexibility to extract outcomes on multiple aspects related to the evaluation of inland shipping emissions and its causes, as demonstrated in Section 3. Finally, implications for policy design are discussed in Section 4.

2. Materials and Methods

2.1. Emission Estimation Method

A comparison between multiple energy and emission estimate approaches for inland waters was made by PIANC-InCom-WG229 [26], indicating that most approaches incorporate engine and ship specifications. In this study, we implement the Python-based

OpenTNSim energy module approach [27], because it was found to be the only approach taking into account corridor stretch specifications and local environmental conditions [26]. The theoretic foundation of this approach is briefly described in Appendix A. For an extensive description of the method, refer to Segers [28] and van Koningsveld et al. [29]. A case study was performed by Jiang et al. [22], underlining the importance of incorporating local conditions when designing corridor bunkering infrastructure for alternative fuels.

Figure 1 presents a schematic diagram of the emission calculation method. The applied module performs energy consumption and emission calculations for a time delta of one vessel at a constant speed. Vessel resistance calculations are the starting point of the approach, as originally suggested by Holtrop and Mennen [30], with corrections by Karpov as described by Terwisga [31] and Zeng et al. [32] to account for shallow water effects. Although detailed vessel shape and propulsion characteristics are required for this method, which are mostly unknown, the importance of including shallow water effects has been found to outweigh the details of the hull form [33,34]. Empirical formulations are included in the module to derive various hull-shape coefficients based on a fixed block coefficient of 0.85. The Specific Fuel Consumption (SFC) and emission factors were obtained based on the vessel's engine age and weight class following Ligterink et al. [35]. Emissions were derived based on the calculated instantaneous vessel break power. If, at low speeds, this power was found to be below 5% of the installed power, the engine was assumed to run stationary at this threshold value.

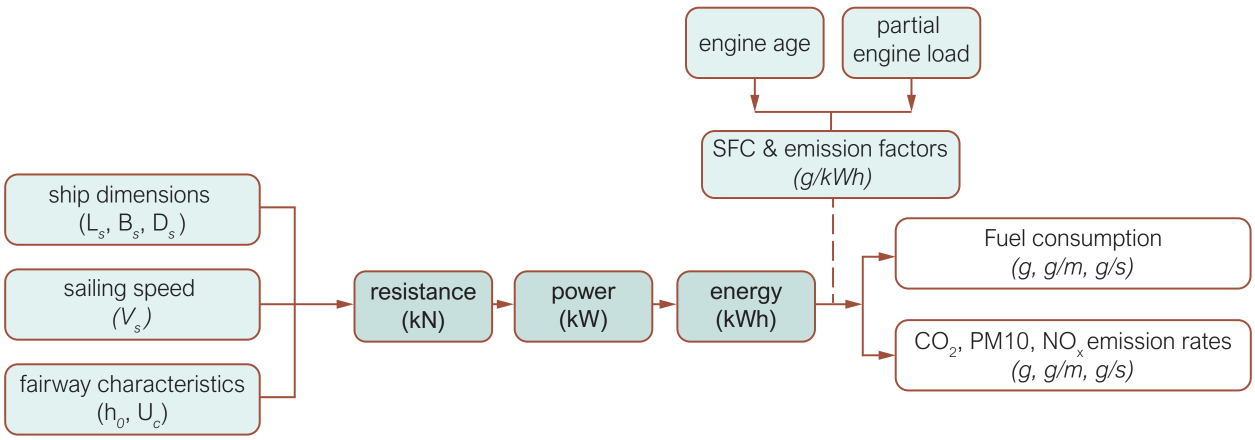


Figure 1. Methodology for estimating emissions for IWT vessels (image modified from Segers [28], 2021, by TU Delft–Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.2. Data Sources

The overview of the utilized data sources is as follows:

AIS data

Following the IMO directive adopted in 2000, larger vessels are required to share data on their position, speed, vessel properties and identity for nautical safety purposes [36]. Historic logs of AIS data can be used to study vessel behavior. Here, we used anonymized AIS data from the entire Dutch inland waterway network for the months of January, April and July of 2019 that were provided by Rijkswaterstaat, the executive agency of the Dutch Ministry of Infrastructure and Water Management that collects these data for the Dutch territory. The data span all Dutch inland waterways, including the "IJsselmeer" and the Eastern and Western Scheldt, directing Antwerp. The AIS data were sorted by vessel identity, resulting in 33,229 vessel tracks, out of which 10,978 could be identified as commercial vessels based on the available vessel type and dimension information.

CEMT classification

The use of anonymized AIS data shields the information on the vessel's identity, which inhibits obtaining this information from other sources. We assumed installed engine power and weight classes from the Conférence Européenne des Minstres de Transports (CEMT) classification as published by Conférence Européenne des Ministres des Transports [37], based on the main dimensions of the vessel.

Engine age distribution

Engine ages, which are important for the emission estimates but generally not known at the fleet level, were estimated from a Weibull distribution, derived by the Dutch Organization for Applied Scientific Research (TNO) from a sample among vessel owners, published by Ligterink et al. [35].

FIS data

Many waterway authorities nowadays share detailed properties of their waterway network through a so-called Fairway Information System (FIS). FIS data can be used to represent a waterway network as a graph of fairway segments (edges) that include properties of the individual fairway segments (width, depth, current). de Jong et al. [38] published a topological fairway network derived from the Dutch FIS [39]. It represents the Dutch fairway network by a graph in which edges represent fairway segments and nodes are located at the edge connections. Edge properties include, among others, linestrings of position coordinates indicating the topology, the segment length, and the limiting CEMT class, which we used as a water depth indicator.

2.3. Designing the Event Table: A Concept for Multi-Perspective Emission Evaluation

Our challenge is to derive inland shipping emission patterns, as well as to create an understanding of the underlying processes and factors causing them. Since these causes are related to the ship's characteristics, the ship's behavior, and the ship's operating conditions that vary in time and space, we need a carefully designed concept that allows us to connect and investigate all of these facets. The applied concept is called an "event table" [40], wherein all data and calculations are gathered and organized.

The event table is inspired by the concepts of moving features and event logs. Moving features are a concept to keep track of a feature, viz. an object with properties, as a function of time and space (see [41]). An event log, used in the field of process mining, is a collection of events, where each 'event' is defined by its 'case', indicating what process the event is part of, and its 'activity', being a well-defined step in the process [42]. The event table has adopted the ability to keep track of time and space from the moving features and the principle of defining events from the event log. The table concept allows for filtering and aggregating operations on the data. The proposed data structure arises from the desire to evaluate the system from multiple perspectives, which is common for systemic approaches [43–45]. Refer to van der Werff et al. [40] for a detailed description.

The design of the event table is considered from four perspectives: scales, conditions, behavior, and dependencies [40], whereby each perspective is used to formulate objectives, and to translate this into design requirements for the event table, refer to Table 2. There are two types of columns in the event table: first, columns that jointly define a unique event (like the case and activity in the event log), and second, columns that provide additional information about each event, called attributes.

Table 3 presents the defined analysis goals for our inland shipping emissions case, together with the specified requirements for the data that we incorporate in the event table. We discuss the choices we made per perspective:

Table 2. Pivoting perspectives used to define requirements to the framework.

Perspective	Requirement	
Scales—The 'where' and 'when' of the performance, uncovering spatial patterns and temporal variations	Fundamental components	The highest level of detail in time (seconds, hours, months, etc.) The highest level of detail in space (meters, street/city/country level, etc.)
	Aggregation means	For deriving time aggregates (hours, days, weeks, months, etc.) For deriving spatial aggregates (street, river, area, state, etc.)
Conditions—Understand how system performance is connected to its underlying processes and their environment	Fundamental components	The highest level of detail of environmental and process description
	Influencing factors	Attributes that indicate influencing factors, and that couple them to performance
Behavior—How the performance of the system is influenced by the behavior of individual agents or collectives	Fundamental components	The highest detail level of individual agent or process to keep track of
	Activity sequence	Means to track the sequence of activities performed by the agent
Dependencies—Identify causal relationships, critical paths, and sensitivities within the entire system	Initiations	Dependency of an event on (an)other event(s)

Table 3. Using pivoting perspectives to define requirements for the scheme of the shipping emissions specifically.

Perspective	Requirement	
Scales—Spatial patterns of inland shipping emissions including hotspots	Fundamental components	Seconds Fairway segment
	Aggregation means	Fairway graph
Conditions—The influence of the environmental conditions on the emissions	Influencing factors	Water depth, current speed, vessel properties
	Coupling factors	Intermediate calculation outcomes
Behavior—Understand how vessel behavior contributes to the emissions	Agent identity	Vessel identity, trip and activity (sailing or pausing)
	Activity sequence	Time stamps
Dependencies—Not considered	Initiations	-

Scales

We have to decide how far we want to be able to zoom in and how we can link the detail level and the higher levels up to the system level. AIS data are very fine-grained but have no means for aggregation in themselves. Furthermore, the environmental conditions are not available at this detail level, being in the order of several 10–100 m. Therefore, we chose the FIS graph as a spatial hierarchic structure, placing the individual fairway segments in the entire Dutch fairway network. Consequently, the AIS data need to be aggregated to the fairway-segment level as well. This is described in Section 2.4. Given that a vessel may cross a fairway segment in less than a minute, we want the time stamps to have at least an accuracy in the order of seconds.

Conditions

Identified influencing factors are the current speed and water depth, as well as the vessel characteristics. This drove the choice for the energy module calculation tool (refer to Section 2.1) and its input dependencies, as presented in Figure 1. Ship dimensions were extracted from AIS. In case of incompleteness, we turned to the CEMT classification. Vessels without any dimension data were excluded from analysis, as indicated in Section 2.2. Unfortunately, vessel draughts indicated in AIS data were often found to be missing or unreliable, which forced us to assume a draught based on the CEMT-class draught range in these cases. The sailing Speed Over Ground (SOG) was extracted from AIS vessel trajectories.

Fairway characteristics were extracted from the FIS [39], with the exception of the water current, which was not available. Therefore, an estimate was made by determining the difference between the velocities of upstream and downstream traveling vessels for each time window of four hours. Having anonymized AIS data obstructed coupling tracks with vessel identities and engine characteristics. Therefore, for each vessel, an engine age was assigned by drawing from a Weibull distribution [35], which was derived based on a survey of inland-vessel ship owners. Furthermore, the installed power (used together with the instantaneous power to determine the partial engine load) and the weight class were assumed based on the CEMT class of the vessel. All intermediate results in the emission calculation process are required as attributes to be able to understand how sub-processes contribute to the calculated emission total.

Behavior

From the behavior perspective, we formulated the requirement that the emissions at the fairway levels should also be traced back to a vessel identity. Moreover, we additionally want to distinguish between various trips of a vessel to account for trip-specific vessel characteristics like draught and cargo. Lastly, we want to trace back what a vessel is actually doing. For this, we have limited information, and using the tools available, we can only differentiate between vessels that are pausing (having a (near-)zero SOG) and vessels that are sailing (having a non-zero SOG).

Time stamps will be used to keep track of the sequence of activities that a vessel performs, i.e., the sequence of fairway segments that it travels. This allows for investigating individual or joint behavior of vessels sailing particular routes with predefined origins and destinations.

Dependencies

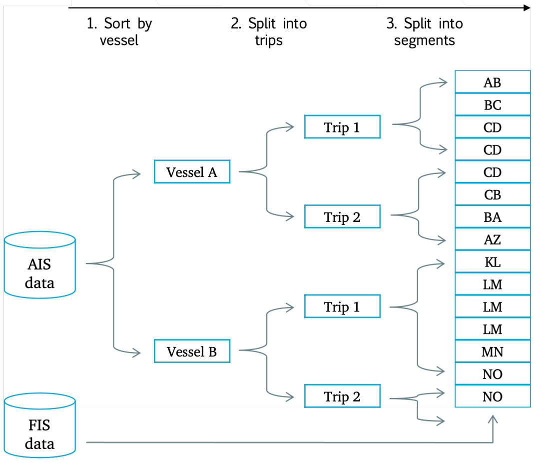
We decided not to consider the dependencies perspective. We do not have any data tying individual vessel actions to the actions of other vessels, and we do not believe that the added value of retrieving this information through simulations balances against the required effort.

Based on the above decisions for each perspective, the event table was designed. A unique event is defined by considering all fundamental components, resulting in the following three variables: fairway segment, vessel trip, and time stamp. As all environmental conditions are connected to the fairway segment, this is considered a fundamental component. The same goes for all vessel characteristics that are tied to one trip of one specific vessel. The time stamp ensures that two activities of a single vessel taking place on a single fairway segment can be distinguished, for example, when a vessel is first pausing on the segment and subsequently sails over that same segment. These three variables are the event-identifying columns in the table, jointly determining the number of events, hence, the length of the table. All other variables indicated are stored as attributes for each event.

Besides the possibilities, these considerations also reveal the limitations of the available set of materials. For example, the absence of reliable draught data forces making assumptions, although this is an important driver for the energy use of a vessel [22]. Furthermore, the anonymous AIS data prohibit coupling vessel tracks with other sources providing more accurate vessel characteristics, such as engine properties or transported cargo.

2.4. Computing Event-Based Inland Shipping Emissions

To construct the event table, first, events were created representing the rows, and second, the emission calculation was performed to derive the emissions for each row in the table, whereby these were added to the table as attribute columns. Figure 2 schematically presents how the event table rows were constructed by creating events, being unique combinations of vessel trip, fairway segment, and time stamp. Herein, first, AIS data were sorted by vessel identity and filtered as described in Section 2.2. Second, the vessel tracks were split into trips using the Python package MovingPandas (version 0.14) based on a time difference in between two subsequent AIS samples in the vessel track exceeding 60 min or by a cluster of multiple subsequent samples located within a diameter of less than 25 m exceeding 60 min. Figure 3a presents AIS vessel tracks, indicating different vessel trips by different colors.



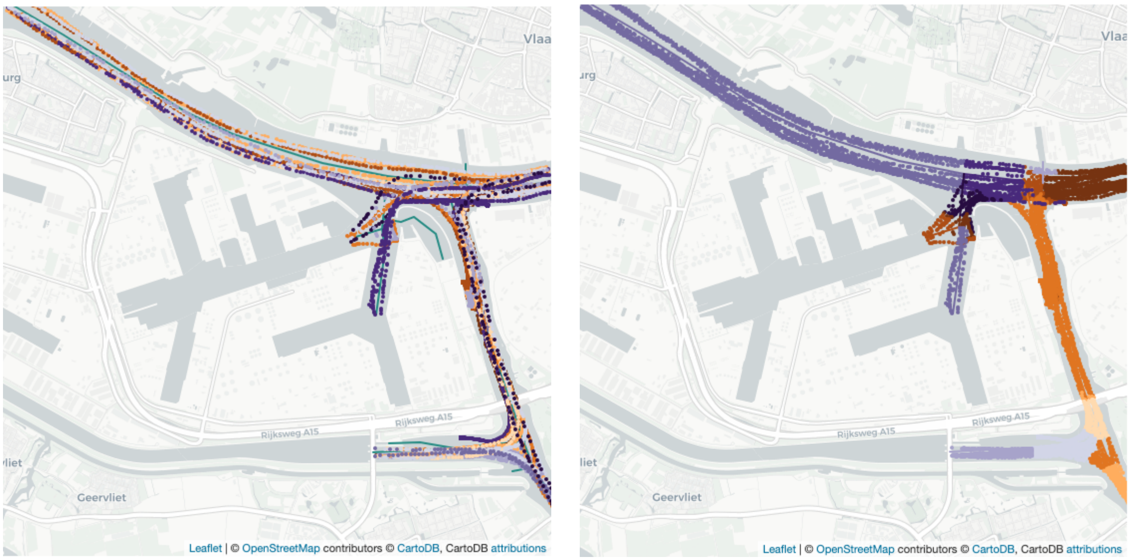
	Event ID			Attributes	
	Vessel Trip	Fairway segment	Instant	Path	…
1	Vessel A - Trip 1	AB	06:00		
2	Vessel A - Trip 1	BC	06:10		
3	Vessel A - Trip 1	CD	06:15		
4	Vessel A - Trip 1	CD	06:20		
5	Vessel A - Trip 2	CD	08:40		
6	Vessel A - Trip 2	CB	08:55		
7	Vessel A - Trip 2	BA	09:05		
8	Vessel A - Trip 2	AZ	09:10		
9	Vessel B - Trip 1	KL	13:30		
10	Vessel B - Trip 1	LM	13:40		
11	Vessel B - Trip 1	LM	13:45		
12	Vessel B - Trip 1	LM	14:10		
13	Vessel B - Trip 1	MN	14:15		
14	Vessel B - Trip 1	NO	14:25		
15	Vessel B - Trip 2	NO	15:30		

Figure 2. Creating the events as rows of the event table, with the schematic process of breaking down vessel data into events (**left**) and the simplified presentation of the resulting event table (**right**).

Third, each trip was split into paths coinciding with a fairway segment as represented by an edge in the FIS graph. Figure 3b presents AIS vessel tracks, indicating the fairway segment the vessel is located on by different colors. To conduct this, AIS samples were identified as a checkpoint following Andrienko and Andrienko [46]. Dijkstra routes were calculated between the closest nodes to the checkpoints in the FIS graph, and these were used to determine the closest edge to each of the samples in the AIS trip coordinates, thereby reducing computational effort as only a subset of the entire graph needed to be considered. Figure 2 presents a simplified event table, indicating each unique event to be a unique combination of vessel trip, fairway segment and time stamp. All events belonging to the same vessel trip have the same color in Figure 3a, and all events located at the same fairway segment have the same color in Figure 3b. The time stamp in the event table is equal to the time stamp of the first AIS sample in the path.

Starting from this event table layout, all the required input for the emission calculation, as described in Section 2.1, could be added as attributes to the table columns: based on the vessel trip data, vessel characteristics could be added, based on the AIS path, the sailing speeds could be derived, and based on the combination of fairway segment and time stamp, instantaneous local conditions could be found. The only intermediate step before running the calculation schematized in Figure 1, was to derive the STW by correcting the SOGs for the speed of the current. Therefore, we estimated the water current speed on each fairway segment by aggregating the mean vessel SOGs over a time span of 12 h and comparing these velocities for upstream and downstream traveling vessels. For tidal waters like the Scheldt estuary, we used a time span of 2 h and combined multiple fairway segments to have sufficient data. The current speeds were used to correct the vessel SOGs, resulting in vessel STW.

The emissions were calculated by applying the process in Figure 1 for each pair of AIS samples, resulting in arrays of resistance values, power values and emission values. Finally, the aggregates were calculated for each event. Input variables, as well as intermediate calculation results, were added to the attribute columns of the event table. Emissions were determined for each event, regardless of the potential idle time. By filtering on the duration and mean speed of the events, an assumed cutoff time for engine shutdown could be applied. All data processing was conducted using Microsoft Planetary Computer [47]. Thereby, computation times were reduced from several days to several hours. After all the processing, we obtained an event table consisting of over 10.1 million rows and 52 columns.



(**a**) (**b**)

Figure 3. AIS data categorizations. (**a**) AIS data categorized by sailing trip (indicated with different colors) (**b**) AIS data categorized by fairway segment (indicated with different colors).

3. Results

This section shows how the event table constructed in Section 2 can be used to analyze shipping emission patterns and connect these patterns with the underlying mechanisms. We present a couple of results from the various pivoting perspectives that were included in the event table design: viz. scales, conditions and behavior.

Scales

Looking at the Dutch inland vessel emissions from the scales perspective is the most straightforward way to connect system-level patterns to contributions of individual vessels. The key is to zoom out and zoom in on space and time. Figure 4 presents the means of the total sailed distance by weekday, presented for the three evaluated months separately. It shows a similar distribution of shipping activities in April and July and a deviating distance for January. The cause is found in New Year's Day (a public holiday on 1 January), falling on a Tuesday. The sailed distance was only 25% of the distance normally sailed on Tuesdays.

To a limited extent, this was visible for the other days in that first week of the year. The same trends were observed for the emissions. Figure 5 shows the distribution of the total shipping emissions over the fairway network, using color and line thickness to indicate the emission levels for CO_2 and PM_{10}. The emissions are presented in grams per kilometre to enable a comparison between fairway segments of varying lengths. The overview allows us to identify hotspots and zoom in to investigate the root causes of these hotspots. The routes that connect Rotterdam, Antwerp and Duisburg can be identified as parts of the network that have the highest emissions. Additionally, a number of hotspots can be recognized in and near ports and locks and at junctions. The hotspots were further investigated by zooming in on the fairway segments contributing most to the CO_2 emissions per traveled kilometer (see Figure 5a). Besides the emissions, other characteristics can be evaluated, like the number of vessel passages or the local conditions at that fairway segment.

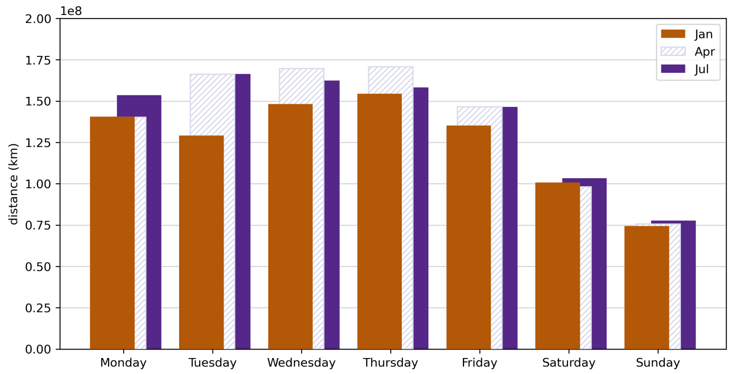
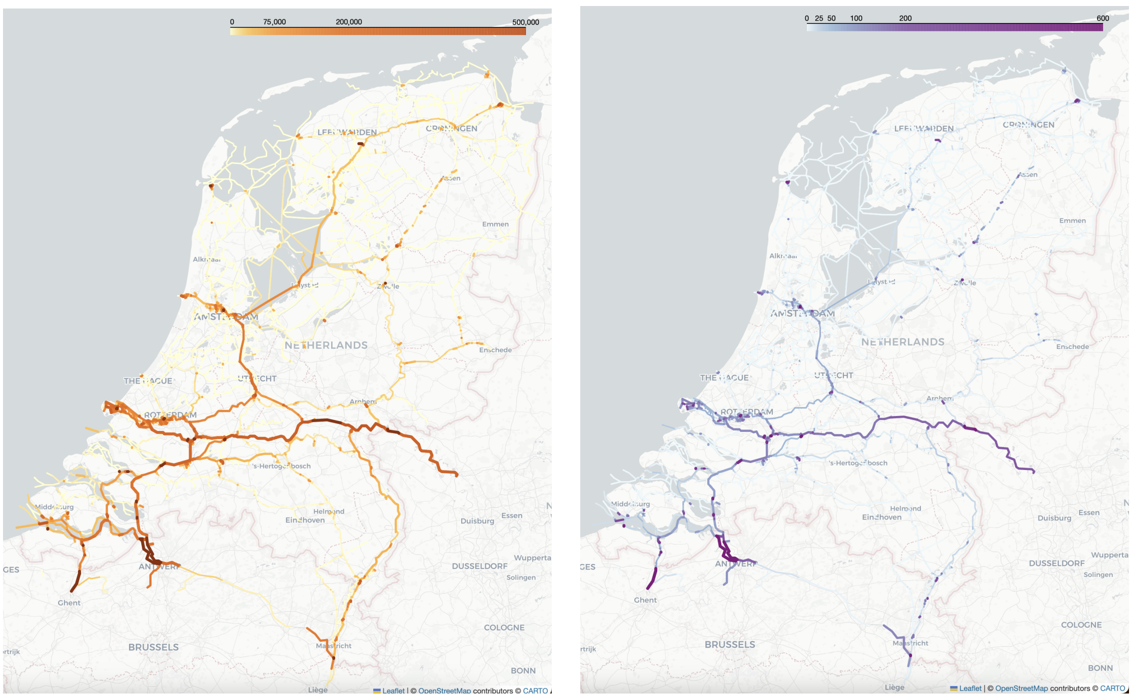


Figure 4. Sailed distances of total fleet in the Netherlands by weekday, monthly means for January, April and July 2019.



(**a**) (**b**)

Figure 5. Map of the Netherlands, indicating the CO_2 and PM_{10} emission levels caused by inland shipping and the most important hotspots. (**a**) CO_2 emission levels (**b**) PM_{10} emission levels.

Conditions

Using the conditions perspective, we delved into the influencing factors of the emissions by addressing two items. First, we considered how environmental conditions affect the shipping emissions, being one of our primary objectives. Second, we investigated the most important contributing factors to hotspots and how much influence they have in the total system. For the first item, we assessed the influence of the current speed and the water depth on the shipping emissions. Figure 6 presents the emissions per distance unit for sections on which currents were present (large rivers). It shows that sailing against the current has a drastic impact on the emissions, almost quadrupling them compared to a near-zero current, while sailing with the current shows to have only a limited effect of 10% at most.

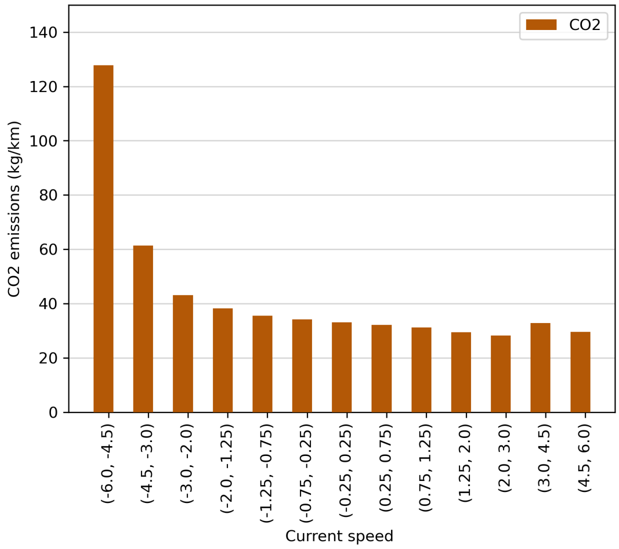


Figure 6. The effect of current on the CO_2 emissions per traveled distance unit.

Figure 7 the fleet types composition (top row), the engine age of the vessels (middle row) and their traveling speed (bottom row), in the appearance of hotspots A and C (river Waal in the left column and Volkerak locks in the middle column, respectively) and for the system as a whole (all Dutch fairways in the right column). Each figure indicates the sailed distance (purple, striped) and the emitted CO_2 mass (brown) per category. For the vessel types, a similar pattern can be seen for both the two hotspots and the total system. The largest vessel class (V) covers the largest distance, but it has a relatively much higher contribution to the emissions. For the second largest class (IV), the share of the total CO_2 emissions is approximately equal to the share of the traveled distance, and the smallest classes emit much less CO_2 compared to the distance they travel. This result can be explained by the fact that larger vessels have a larger resistance to overcome, resulting in higher energy use and higher emissions. Of course, it is noted that the cargo capacity of class V vessels is up to twice that of class IV vessels [48].

Categorizing into engine age classes (middle row in Figure 7) shows that the distribution of engine ages is the same for the vessels at both hotspots and when considering all vessels in the system. Furthermore, the contributions of sailed distance and emissions indicate that vessels with modern engines only emit slightly less CO_2 per sailed kilometer than those with old engines. For the PM_{10} emissions, this distribution is very different, as indicated in Figure 8, where new engines contribute only a fraction of the total PM_{10} emissions, compared to the distance they covered. To understand the uncertainty introduced by assigning engine ages to vessels based on the Weibull distribution [35], we evaluated the emissions for multiple realizations of engine ages for the fleet. It was found that the sum of the emissions in the system varied less than 0.3% for CO_2 and 3.4% for PM_{10} with larger variations locally.

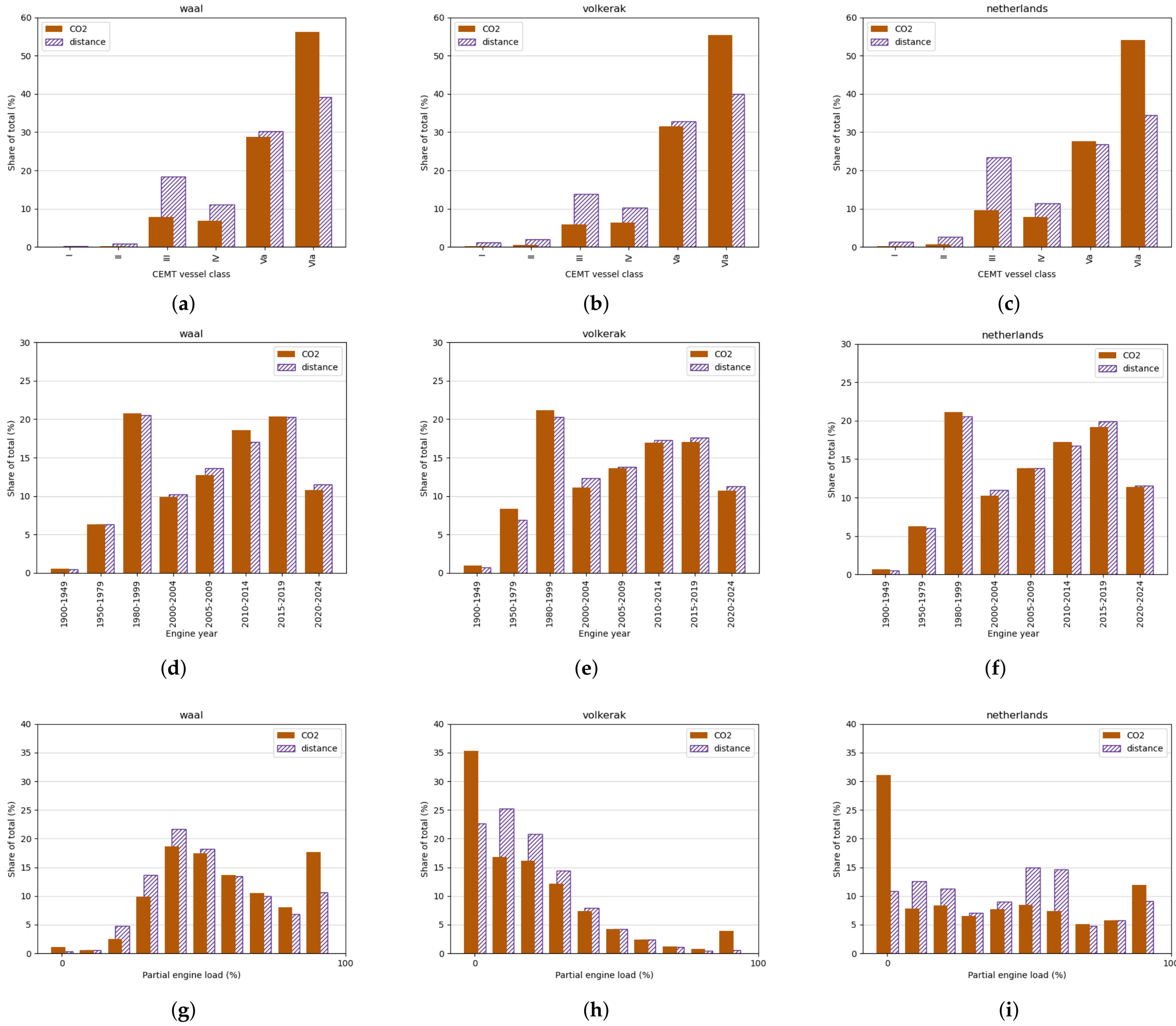


Figure 7. Conditions perspective: understanding causes of emission patterns and hotspots. (**a**) Vessel types (Waal) (**b**) Vessel types (Volkerak) (**c**) Vessel types (Netherlands) (**d**) Engine years (Waal) (**e**) Engine years (Volkerak) (**f**) Engine years (Netherlands) (**g**) Partial engine load (Waal) (**h**) Partial engine load (Volkerak) (**i**) Partial engine load (Netherlands).

Lastly, we categorized into partial engine load, which indicates the throttle setting ranging from neutral (0% of full power) to stationary (10% of full power) to full power (100%). Hence, it is related to the sailing speed. This 0–100% range of engine settings was divided into 10 bins. Two sources of emissions can be distinguished based on this breakdown. On one hand, the emissions arise due to busy traffic at moderate and high sailing speeds. This occurs at the river Waal hotspot, being a continuing shipping route (Figure 7g). On the other hand, the emissions arise due to traffic slowing down, maneuvering, and idling (stationary throttle setting at 10% of full power). This occurs at fairway segments near busy locks and ports (Figure 7h). How much both of these mechanisms influence the emissions in the total system becomes clear from Figure 7i. For high engine powers, the share of emissions is slightly larger than the share of sailed distance. However, about one-third of the emissions is caused by vessels running idle (power in lowest category), while only 11% of the distance is covered using this engine setting.

Sailing at low partial engine loads is inefficient in terms of fuel use and emission production [35]. To better understand how the emissions arise in the lowest engine-setting category, a further breakdown was made in Figure 9. The top chart presents the breakdown of the total CO_2 shipping emissions into the ten engine-setting categories. The middle chart indicates the share of the emissions in the lowest engine-setting category caused by sailing and the share caused by stationary vessels. It shows that only 15% of the emissions within the 0–10% power range is produced while the vessel was actually stationary, and the vast majority is the result of idling vessels. The bottom chart shows how the emissions caused by stationary vessels were further broken down into duration categories, showing how many of them were caused during pauses of a certain length. The maximum length is 4 h, since we assumed that above this threshold, all vessels have switched off their engine. Based on these charts, it can be concluded that assuming all vessels switch off their engine after 2 h only results in less than 2% lower emissions.

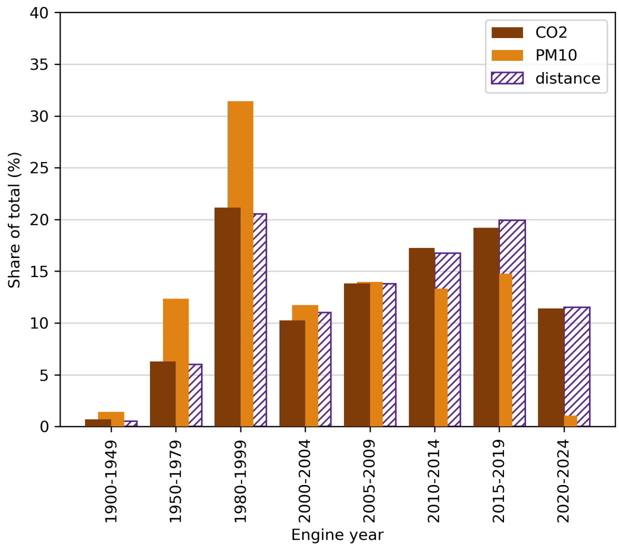


Figure 8. The contributions of various engine age classes on the total CO_2- and PM_{10} emissions.

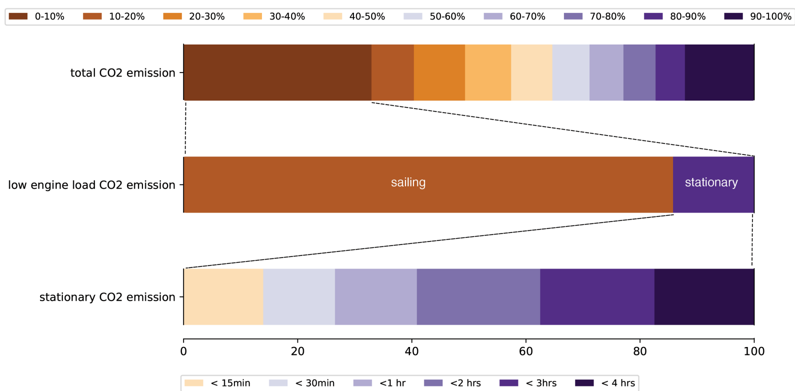


Figure 9. Breakdown of emissions at three levels: (**top**) breakdown of total emissions into partial engine load bins, (**middle**) breakdown of emissions in the lowest bin into status, (**bottom**) breakdown of stationary vessels emissions into duration of pause.

Behavior

The behavior perspective can answer questions related to sailing profiles of vessels and the consequences of their behavior under given environmental conditions, as well as the produced emissions. We evaluated the sequence of activities performed by the vessels to illustrate this perspective. In Figure 10, all trips between Antwerp and Duisburg were evaluated. The horizontal axis represents the route, with Antwerp on the left-hand side (0 km) and Duisburg on the right-hand side (approx. 250 km). Thereby, the characteristics of the vessel trips in both sailing directions can be directly compared, whereby the Antwerp–Duisburg direction is indicated with solid lines and the Duisburg–Antwerp direction is indicated with dotted lines. In green, the plot presents the mean SOGs, obtained from the AIS-signal. In brown, the plot presents the mean speeds corrected for the current (STW). In purple, the plot presents the mean CO_2 emissions per sailed kilometre over the entire route.

On the left-hand side, two lock complexes are encountered, the Kreekrak and Volkerak locks, at 15 and 60 km, respectively. They come forward in Figure 10 through to the dip in mean speeds and the peak in emissions. Between these locks, the trip characteristics are very similar for both traveling directions. On this part of the route, current speeds are negligible, as the mean SOG is equal to the STW. However, a step change can be observed in the CO_2 emissions. This is triggered by a transition from shallow water to fairway segments having larger water depths. The right-hand part of the figure, between 100 and 250 km, represents the river Waal. Here, we observe a difference between the SOG and STW. Vessels sailing against the current (direction Antwerp-Duisburg) have a lower SOG than vessels traveling in the opposite direction. When correcting for the current, speeds in both directions become similar again, although vessels sailing upstream slightly increase power to overcome the current speed (refer to the brown lines in Figure 10). Additionally, due to their longer travel time, vessels sailing upstream produce significantly higher emissions per traveled kilometre than those traveling downstream. Hence, Figure 10 demonstrates that vessels may adjust their behavior to the (changing) environmental conditions, thereby influencing the emission performance.

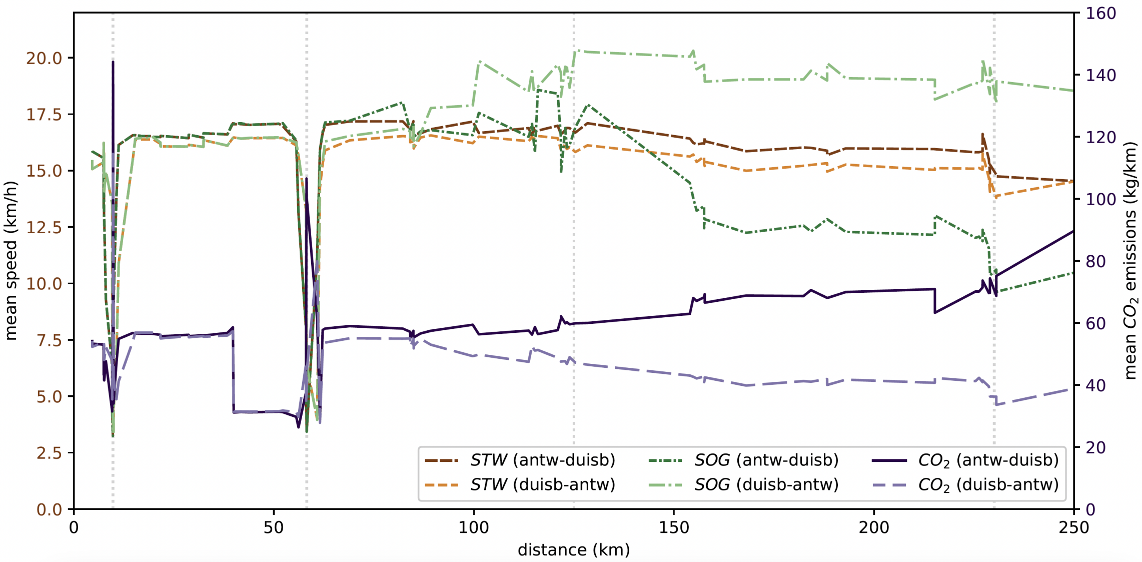


Figure 10. Analysis of vessels traveling between Antwerp and Duisburg, indicating the mean vessel STW (brown), the mean vessel SOG (green), and the mean CO_2 emissions (purple) for vessels sailing from Antwerp to Duisburg (solid) and from Duisburg to Antwerp (dashed). The vertical lines indicate the Kreekrak locks, the Volkerak locks, Gorinchem and Nijmegen from left to right.

4. Discussion

4.1. Contribution to Emission-Reduction Policy Design

In Section 3 we demonstrated a couple of examples out of the large variety of visual outcomes that could be created based on the constructed event table. Based on these outcomes, we are able to address concrete policy-related challenges regarding inland shipping emissions in the Netherlands. For example: what could be done to lower emissions in the identified hotspots? By combining a scales perspective with a conditions perspective, this study underlines that different hotspots have different causes, and therefore, reducing these emissions requires location-specific policies. For example, we have shown that some hotspots occur near locks, where vessels spend a lot of time idling and maneuvering. Globally oriented policies invoking cleaner engines have a limited effect due to the unfavorable power settings during slow sailing. However, targeted measures like optimizing lock passage times for vessels may yield significant emission reductions locally. On the other hand, hotspots at busy rivers like the Waal may have only limited possibilities for emission reduction besides the global measure to renew (old) engines.

Elaborating further on potential measures, like those suggested above: what is then the potential impact of fleet renewal. The challenge is to understand the trade-off between the emission-reductions that can be achieved by renewing a particular (smaller or larger) share of the fleet, and the costs that are involved to do so. Referring to Figure 8, we found that, based on the latest emission factors for engine of a particular age [35], the potential CO_2 emission reduction is limited; even when replacing all engines manufactured before 2000, representing about a third of the fleet, would only potentially reduce those emissions with approximately 1.5%. For PM_{10}, this balance is different; renewing only 6% of the fleet's engines would potentially reduce those emissions with approximately 12.5%.

As stressed by [14], which strategy works varies from corridor to corridor and even from fairway to fairway. So, can the outcomes help identifying Green Shipping Corridor (GSC) or corridors with (at this moment) a higher potential for alternative energy sources? Based on Figure 10, we can grasp the different characteristics of the fairways between Antwerp and Rotterdam and those between Rotterdam and Duisburg. With multiple locks that need to be passed between Antwerp and Rotterdam, this system is characterized as 'closed'. As a consequence, current effects are absent, and furthermore, knowing the detailed bathymetry, resulting in accurate water depth predictions based on actual water levels, makes the energy use on the Antwerp–Rotterdam corridor more predictable than for the Rotterdam–Duisburg route. Moreover, the current on the Rotterdam–Duisburg corridor results in significantly different energy use profiles for upstream- and downstream-sailing vessels, thereby complicating the positioning of charging points or bunker locations. Based on these arguments, the Antwerp-Rotterdam corridor would have a higher potential for testing the use of alternative energy carriers. Note that more specific distance-behavior plots may be made for individual vessels or specific vessel types or groups on a specific corridor for further understanding or comparison.

4.2. Discussion of the Limitations and Future Work

The availability of input materials and tools is a key driver for the obtained outcomes. The data sources and content of the data have resulted in a number of assumptions. These assumptions were regarding vessel characteristics and the emission estimation approach. The resulting limitations to the study are discussed in this section. To outline the impact of the limitations, we have used the event table to indicate the sensitivity of some of these assumptions, for example, for the assumed Weibull distribution for engine ages. To exploit the full potential of the approach in the assessment of inland shipping emissions, we have the following recommendations to reduce the uncertainties related to these assumptions.

The availability of anonymized AIS data has limited the possibilities for coupling vessel behavior from the GPS-tracks to other sources of data, like vessel databases, including vessel dimensions, accurate engine characteristics and ages, and correct vessel operating draughts. Based on non-anonymized data, future studies could, furthermore, make an effort to couple vessel trips to transported cargo, allowing to express emissions in kilograms per tons-distance cargo. With more detailed data on the water depth, better conclusions regarding the influence of shallow water sailing sections on the total of shipping emissions can be drawn, and a more detailed connection with weather conditions could indicate the effect of weather conditions on the vessel behavior (sailing speed or covered distance).

Future research should also expand the amount of data used in the analysis, i.e., the period covered by the AIS data, to improve the robustness of the observed patterns. This would require significant additional computational resources. The use of such resources was not warranted to demonstrate the workings of the method proposed here but would be recommended for a thorough policy management study.

Furthermore, an important limitation of the study is that the applied approach for resistance calculation was primarily developed for seagoing vessels, and therefore, it is less suitable for inland vessels and barges, having a higher block coefficient. Although the literature states that the incorporation of shallow water effects outweighs shape-related input uncertainties, future work should include undertaking further validation and investigating the extrapolation of the approach to vessels with higher block coefficients.

We have shown that the presented approach, using an event table and evaluating a system from several perspectives, is very suitable to address a range of other types of problems that consider complex systems whereby spatial variations influence the behavior and/or performance of an agent in the system, and where many different choices for interventions may be made. The evaluation of the inland shipping emissions is a relatively straightforward application since the attributes in the event table depend on a single vessel. Other applications might demand incorporating vessel-vessel interactions. For example, when considering nautical safety, AIS data can be used to evaluate distances and interactions between vessels. The event table is then required to capture the behaviors of vessel pairs instead of just individual vessels. When considering locking operations, the performance of the locking procedure strongly depends on the interaction of multiple vessels in the same locking cycle and their influence on each other's waiting times.

5. Conclusions

Shipping-related policies require an in-depth understanding of performance patterns at the system level, supported by insights into underlying processes. The existing approaches to evaluate the inland shipping system (and many other systems) make it impossible to change perspective flexibly between that of the entire system and those capturing how individual or groups of agents behave and the conditions they encounter. By using the event-table scheme, we are now able to bring each of these perspectives together, making it straightforward to tie observations in one perspective (for example, spatial patterns on a map) to supporting explanations based on another perspective (for example, vessel speeds and their contributions to emissions). This provides an essential understanding of how the system works and how the most promising improvements can be identified.

A thorough evaluation of the spatial emissions patterns on the Dutch inland waterways at various levels showed the important contributions of two phenomena: first, most hotspots are caused by large amounts of vessels sailing slow, running idle, or waiting, near locks and ports, and second, some hotspots occur at continuing rivers and channels with busy traffic at moderate speeds to full power. We presented the spatial patterns both for CO_2 and PM_{10} emissions, whereby the high-level views were similar. However, the policies related to reducing either of them are likely very different, firstly because CO_2 is much more considered at a global level while PM_{10} has a more concentrated (local) impact, and secondly because the PM_{10} reductions that can be obtained with engine renewal are much more significant than the CO_2 reductions for this measure.

In search of other potential measures, we found that a low engine speed setting is responsible for about a third of all CO_2 emissions, and further breakdowns indicated that only a minority share (15%) of these emissions are caused by vessels that actually lay still. Hence, idling, slowing down, and maneuvering contribute significantly to the total emissions caused by inland vessels. We shed light on the root causes of inland shipping emissions, enabling data-driven or data-supported decision-making instead of relying purely on expert opinions. By zooming in on the Antwerp–Duisburg corridor, we gained an understanding of the role of infrastructure like locks, the influence of environmental conditions like currents, and the (adjusted) behavior of vessels. Moderate current speeds can already cause CO_2 emissions per kilometre of upstream vessels to be a factor of 1.75 of the downstream vessels. Moving from relatively deep to shallow water causes a CO_2 emission increase of 50% when the vessel power is not adjusted.

Hence, our approach contributes to tackling the three identified challenges related to policy design for emission reductions. First, by taking different angles, a better understanding can be obtained of the implications that designed measures may have, both locally and at the system level, as was discussed in Section 4.1. Second, the fact that spatial- and time-varying circumstances can be factored in facilitates that measures and policies are better adjusted to local fairway characteristics. Third, having the obtained flexibility ensures well-understood operational profiles for individual vessels, groups of vessels, or routes that are required when developing new vessel technologies.

Author Contributions: Conceptualization, S.v.d.W., F.B. and M.v.K.; methodology, S.v.d.W.; software, S.v.d.W. and F.B.; validation, S.v.d.W. and M.v.K.; formal analysis, S.v.d.W.; data curation, S.v.d.W. and F.B.; writing—original draft preparation, S.v.d.W.; writing—review and editing, F.B. and M.v.K.; visualization, S.v.d.W.; supervision, F.B. and M.v.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by SmartPort, the knowledge hub of the Port of Rotterdam.

Data Availability Statement: The datasets presented in this article are not readily available because privacy restrictions apply to the raw and processed data. Aggregated data presented in this study are available on request from the corresponding author. Programming code is openly available in Github at https://github.com/sevanderwerff/system-emissions (accessed on 4 March 2025).

Acknowledgments: The authors thank Rijkswaterstaat for providing AIS data for this study.

Conflicts of Interest: Mark van Koningsveld was employed by Van Oord Dredging and Marine Contractors B.V. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AIS	Automatic Identification System
CEMT	Conférence Européenne des Minstres de Transports
FIS	Fairway Information System
GSC	Green Shipping Corridor
IMO	International Maritime Organisation
LNG	Liquefied Natural Gas

SFC	Specific Fuel Consumption
SOG	Speed Over Ground
STW	Speed Through Water

Appendix A. Vessel Energy Use Calculation

The basic idea of the approach is that it is possible to estimate the total resistance (kN) that a vessel experiences for known vessel characteristics (length, beam, draught, vessel SOG) and fairway properties (channel width, depth and ambient current). Following the empirical approach of Holtrop and Mennen [30], the resistance is estimated through a summation of the frictional resistance R_F, the appendage resistance R_{app}, the resistance due to the generation of waves R_W, the residual resistance R_{res} and the ship-model correlation resistance R_A, as indicated in Equation (A1). Furthermore, $(1 + k_1)$ represents the form factor introducing the viscous resistance component. Shallow water corrections were made in the frictional resistance and in the wave resistance. Note that these corrections can only be applied if both the instantaneous vessel SOG, the local water depth, and the current speed at that moment in time are known.

$$R_{tot} = R_F(1 + k_1) + R_{app} + R_W + R_{res} + R_A \quad \text{(A1)}$$

The effective horsepower P_e is the power required to overcome the vessel resistance R_{tot} based on the vessel's STW V_0, refer to Equation (A2). Accounting for the losses at the propeller, shaft and gearbox results in the break horsepower P_b that the engine should deliver. Refer to Equation (A3), whereby η_t and η_g are the transmission and gearing efficiencies, respectively, and η_0, η_r and η_h are the propeller open water efficiency, the relative rotative efficiency and the hull efficiency, respectively. All efficiencies were assumed constant and independent of the considered vessel. Adding the hotel power to the break horse power results in the total power P_{tot} (Equation (A4)), whereby the hotel power is estimated constant at 5% of the installed engine power.

$$P_e = V_0 \cdot R_{tot} \quad \text{(A2)}$$

$$P_b = P_e \left(\frac{1}{\eta_t \eta_g} \right) \left(\frac{1}{\eta_0 \eta_r \eta_h} \right) \quad \text{(A3)}$$

$$P_{tot} = P_b + P_{hotel} \quad \text{(A4)}$$

The product of the total power and the duration Δt that it needs to be delivered yields the energy E (kWh) that is associated with that sailing event:

$$E = P_{tot} \cdot \Delta t \quad \text{(A5)}$$

The vessel weight class combined with the engine age result in an estimate for the general emission factor EF_{gen} [35]. Furthermore, estimates of the partial engine load, calculated as power demand over installed power, were used to determine an emission correction factor EF_{corr}, to capture the effect that engines produce more emissions when they are run outside their optimal operating specification. These emission factors are used to estimate the potential emission EM of green house gasses (i.e., CO_2) and other environmental pollutants (i.e., PM_{10}, NO_X), refer to Equation (A6). We state 'potential' emissions, since actual emissions depend on the installation of mitigating measures, like scrubbers and filters.

$$EM = E \cdot EF_{gen} \cdot EF_{corr} \quad \text{(A6)}$$

References

1. United Nations/Framework Convention on Climate Change. Adoption of the Paris Agreement. In Proceedings of the 21st Conference of the Parties, Paris, France, 12 December 2015; United Nations: New York, NY, USA, 2015; Ch. UNTC XXVII 7.d.
2. European Commission. The European Green Deal. Bill. 2019. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 4 March 2025).
3. Marine Environment Protection Committee. *RESOLUTION MEPC.304(72)—Adoption of the Initial IMO Strategy on Reduction of GHG Emissions from Ships*; Resolution; Marine Environment Protection Committee: London, UK, 2018.
4. Dutch Inland Shipping Green Deal. Green Deal on Maritime and Inland Shipping and Ports. Bill, The Hague. 2019. Available online: https://www.greendeals.nl/sites/default/files/2019-11/GD230%20Greenf%20Deal%20on%20Maritime%20and%20Inland%20shipping%20and%20Ports.pdf (accessed on 4 March 2025).
5. Minister of Infrastructure and Water Management. *Subsidieverlening Zero Emission Services, Aanleg Laadstations en Aanschaf Energiecontainers*; Decree; Minister of Infrastructure and Water Management: The Hague, The Netherlands, 2022.
6. Song, Z.-Y.; Prem Chhetri, G.Y.; Lee, P.T.W. Green maritime logistics coalition by green shipping corridors: A new paradigm for the decarbonisation of the maritime industry. *Int. J. Logist. Res. Appl.* **2023**, *28*, 363–379. [CrossRef]
7. Port of Rotterdam. Partners Launch Condor H2 for Emission-Free Inland and Near-Shore Shipping. 2023. Available online: https://www.portofrotterdam.com/en/news-and-press-releases/whs2023-partners-launch-condor-h2-for-emission-free-inland-and-near-shore (accessed on 20 June 2024).
8. Luo, X.; Yan, R.; Wang, S. Ship sailing speed optimization considering dynamic meteorological conditions. *Transp. Res. Part C Emerg. Technol.* **2024**, *167*, 104827. [CrossRef]
9. Jiang, H.; Peng, D.; Wang, Y.; Fu, M. Comparison of inland ship emission results from a real-world test and an ais-based model. *Atmosphere* **2021**, *12*, 1611. [CrossRef]
10. Kurtenbach, R.; Vaupel, K.; Kleffmann, J.; Klenk, U.; Schmidt, E.; Wiesen, P. Emissions of NO, NO2 and PM from inland shipping. *Atmos. Chem. Phys.* **2016**, *16*, 14285–14295. [CrossRef]
11. Eger, P.; Mathes, T.; Zavarsky, A.; Duester, L. Measurement report: Inland ship emissions and their contribution to NOx and ultrafine particle concentrations at the Rhine. *Atmos. Chem. Phys.* **2023**, *23*, 8769–8788. [CrossRef]
12. Krause, K.; Wittrock, F.; Richter, A.; Busch, D.; Bergen, A.; Burrows, J.P.; Freitag, S.; Halbherr, O. Determination of NOx emission rates of inland ships from onshore measurements. *Atmos. Meas. Tech.* **2023**, *16*, 1767–1787. [CrossRef]
13. Keuken, M.P.; Moerman, M.; Jonkers, J.; Hulskotte, J.; van der Gon, H.A.D.; Hoek, G.; Sokhi, R.S. Impact of inland shipping emissions on elemental carbon concentrations near waterways in The Netherlands. *Atmos. Environ.* **2014**, *95*, 1–9. [CrossRef]
14. PIANC InCom. *WG234 Infrastructure for the Decarbonisation of IWT*; Report, PIANC-InCom-WG234; PIANC InCom: Brussels, Belgium, 2023.
15. Fan, A.; Wang, J.; He, Y.; Perčić, M.; Vladimir, N.; Yang, L. Decarbonising inland ship power system: Alternative solution and assessment method. *Energy* **2021**, *226*, 120266. [CrossRef]
16. Evers, V.; Kirkels, A.; Godjevac, M. Carbon footprint of hydrogen-powered inland shipping: Impacts and hotspots. *Renew. Sustain. Energy Rev.* **2023**, *185*, 113629. [CrossRef]
17. Fan, A.; Xiong, Y.; Yang, L.; Zhang, H.; He, Y. Carbon footprint model and low–carbon pathway of inland shipping based on micro–macro analysis. *Energy* **2023**, *263*, 126150. [CrossRef]
18. Tan, Z.; Zeng, X.; Shao, S.; Chen, J.; Wang, H. Scrubber installation and green fuel for inland river ships with non-identical streamflow. *Transp. Res. Part E Logist. Transp. Rev.* **2022**, *161*, 102677. [CrossRef]
19. Gao, D.; Zhang, W.; Shen, A.; Wang, Y. Parameter design and energy control of the power train in a hybrid electric boat. *Energies* **2017**, *10*, 1028. [CrossRef]
20. Zhang, Y.; Sun, L.; Fan, T.; Ma, F.; Xiong, Y. Speed and energy optimization method for the inland all-electric ship in battery-swapping mode. *Ocean Eng.* **2023**, *284*, 115234. [CrossRef]
21. Ahamad, N.B.B.; Guerrero, J.M.; Su, C.L.; Vasquez, J.C.; Zhaoxia, X. Microgrids Technologies in Future Seaports. In Proceedings of the 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Palermo, Italy, 12–15 June 2018; pp. 1–6. [CrossRef]
22. Jiang, M.; Baart, F.; Visser, K.; Hekkenberg, R.; Van Koningsveld, M. Corridor Scale Planning of Bunker Infrastructure for Zero-Emission Energy Sources in Inland Waterway Transport. In *Proceedings of PIANC Smart Rivers 2022*; Li, Y., Hu, Y., Rigo, P., Lefler, F.E., Zhao, G., Eds.; Springer Nature: Singapore, 2023; pp. 334–345. [CrossRef]
23. Šimenc, M. Overview and comparative analysis of emission calculators for inland shipping. *Int. J. Sustain. Transp.* **2016**, *10*, 627–637. [CrossRef]
24. Goldsworthy, L.; Goldsworthy, B. Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data—An Australian case study. *Environ. Model. Softw.* **2015**, *63*, 45–60. [CrossRef]
25. Jalkanen, J.P.; Johansson, L.; Kukkonen, J.; Brink, A.; Kalli, J.; Stipa, T. Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. *Atmos. Chem. Phys.* **2012**, *12*, 2641–2659. [CrossRef]

26. PIANC InCom. *Guideline for Air Pollutants and Carbon Emissions Performance Indicators for Inland Waterways*; Report, PIANC-InCom-WG229; PIANC InCom: Brussels, Belgium, 2024.
27. Jiang, M.; Segers, L.; van der Werff, S.; Baart, F.; van Koningsveld, M. OpenTNSim, Version v1.1.1. *Zenodo* **2022**. [CrossRef]
28. Segers, L. Mapping Inland Shipping Emissions in Time and Space for the Benefit of Emission Policy Development. Master's Thesis, Delft University of Technology, Delft, The Netherlands, 2021.
29. van Koningsveld, M.; van der Werff, S.; Jiang, M.; Lansen, J.; de Vriend, H. *Ports and Waterways—Navigating the Changing World*; Chapter Performance of Ports and Waterway Systems; TU Delft Open: Delft, The Netherlands, 2021; pp. 433–458. [CrossRef]
30. Holtrop, J.; Mennen, G. A statistical Power Prediction Method. *Int. Shipbuild. Prog.* **1978**, *25*, 253–256.
31. Terwisga, T. *Weerstand en Voortstuwing van Bakken: Een Literatuurstudie*; Technical Report 49199-1-RD; Maritiem Research Instituut Nederland: Wageningen, The Netherlands, 1989.
32. Zeng, Q.; Thill, C.; Hekkenberg, R.; Rotteveel, E. A modification of the ITTC57 correlation line for shallow water. *J. Mar. Sci. Technol.* **2019**, *24*, 642–657. [CrossRef]
33. Hofman, M.; Kozarski, V. Shallow Water Resistance Charts for Preliminary Vessel Design. *Int. Shipbuild. Prog.* **2000**, *47*, 61–76.
34. Hekkenberg, R.G. Inland Ships for Efficient Transport Chains. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2013. [CrossRef]
35. Ligterink, N.; van Gijswijk, R.; Kadijk, G.; Vermeulen, R.; Indrajuana, A.; Elstgeest, M. *Emissiefactoren Wegverkeer—Actualisatie 2019*; Technical Report 2019-STL-RAP-100321751; TNO: Den Haag, The Netherlands, 2019.
36. Maritime Safety Committee. *RESOLUTION MSC.74(69)*; Resolution; Maritime Safety Committee: London, UK, 1998.
37. Conférence Européenne des Ministres des Transports. *Resolution No. 92/2 on New Classification of Inland Waterways*; Statute; Conférence Européenne des Ministres des Transports: Bruxelles, Belgium, 1992.
38. de Jong, J.; Baart, F.; Zagonjolli, M. *Topological Network of the Dutch Fairway Information System*, Version v0.2.0; Zenodo: Geneva, Switzerland, 2021. [CrossRef]
39. Rijkswaterstaat. Fairways and Infrastructure Netherlands. 2024. Available online: https://www.vaarweginformatie.nl (accessed on 20 June 2024).
40. van der Werff, S.; van Gelder, P.; Baart, F.; van Koningsveld, M. How Early Integration of Multiple Analysis Perspectives Can Enhance the Understanding of Complex Systems. 2025, *in preparation*. [CrossRef]
41. Asahara, A.; Hayashi, H.; Ishimaru, N.; Shibasaki, R.; Kanasugi, H. International Standard "OGC Moving Features" to address "4Vs" on locational BigData. In Proceedings of the 2015 IEEE International Conference on Big Data (Big Data), Santa Clara, CA, USA, 29 October–1 November 2015; pp. 1958–1966.
42. van der Aalst, W. Process Mining. *ACM Trans. Manag. Inf. Syst.* **2012**, *3*, 2. [CrossRef]
43. Smyth, D.; Checkland, P. Using a Systems Approach: The Structure of Root Definitions. *J. Appl. Syst. Anal.* **1976**, *5*, 75–83.
44. Bunge, M.A. *Treatise on Basic Philosophy: Ontology II: A World of Systems*; Reidel Publishing Company: Dordrecht, The Netherlands, 1979.
45. Lukyanenko, R.; Storey, V.C.; Pastor, O. System: A core conceptual modeling construct for capturing complexity. *Data Knowl. Eng.* **2022**, *141*, 102062. [CrossRef]
46. Andrienko, N.; Andrienko, G. Article Visual analytics of movement: An overview of methods, tools and procedures. *Inf. Vis.* **2013**, *12*, 3–24. [CrossRef]
47. Microsoft Open Source; McFarland, M.; Emanuele, R.; Morris, D.; Augspurger, T. *microsoft/PlanetaryComputer: October 2022*, Version 2022.10.28; Zenodo: Geneva, Switzerland, 2022. [CrossRef]
48. Rijkswaterstaat. *Richtlijnen Vaarwegen 2020*; Rijkswaterstaat Water, Verkeer en Leefomgeving: Rijswijk, The Netherlands, 2020.