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A framework for automated digital reporting of directly measured ships' CO_2 emissions

Adrian Freiter[1*] and Hannah Pache[2]

[1] Industrial Manufacturing, Fraunhofer Institute for Software and Systems Engineering, Dortmund, Germany
[2] Sea Traffic and Nautical Solutions, Fraunhofer Center for Maritime Logistics and Services, Hamburg, Germany

[*]E-mail: adrian.freiter@isst.fraunhofer.de

Abstract. Ship owners must report their greenhouse gas emissions to the relevant authorities. Currently, data collection is manual and inconsistent. A proposed automated framework uses sensors to directly measure CO_2 emissions, thereby enhancing accuracy and reducing manual effort. The system validates the sensor data and collects meta-information (e.g. ship position, weather), aggregating it for analysis. The validated data is then forwarded to classification societies for reporting purposes. This framework supports both autonomous and existing vessels and allows for retrofitting to ensure compliance with emissions reporting standards. This paper reviews the existing literature and outlines the requirements for designing the proposed framework, as well as discussing its potential and risks.

1. Introduction

Although seaborn transport is considered the most environmentally friendly mode per ton-mile [1], shipping (including international, domestic and fishing) is still responsible for around 2.89 % of the worldwide greenhouse gas (GHG) emissions [2]. Because shipping contributes significantly to climate change, the International Maritime Organization (IMO) and the European Union (EU) introduced guiding regulations to cut the carbon emissions. These measures create incentives to reduce GHGs but also impose extensive reporting requirements on shipowners.

These regulations rely on taxes and fees and thus creating financial incentives to minimise emissions. This creates the need for ship owners to measure and report emissions precisely to avoid paying more than necessary. Current CO_2 emissions reporting practices rely on manual approaches, which can be error prone. Usually, estimation factors are used to calculate the CO_2 emissions leaving room for improvement. Automating reporting and measuring CO_2 emissions directly can increase accuracy while decreasing workload and the potential for errors or manipulation. Since human errors are the most significant cause of errors in the data. Additionally, automated and digital reporting of ships' CO_2 emissions will enable shipowners to easily measure and verify emissions for surplus emission trading, as planned by the IMO, which is expected to come into force in 2027 [3].

This paper is structured as follows. Section 2 explains the regulatory frameworks and existing research as well as the resulting research gap. Section 3 then describes the approach to the framework for automated digital reporting of directly measured ships' CO_2 emissions. The paper concludes with a section on discussion and a section on conclusions and outlook.

2. Background

This paper focuses on the CO_2 emission reporting, since it is currently required by reporting schemes. However, the concept should be generally adaptable to the reporting of other GHG emissions such as CH_4, N_2O as well as particulate matter (SO_x, NO_x).

At the international level, the IMO has introduced the data collection system (DCS). The IMO DCS has had its first reporting period in 2020 and requires the yearly fuel consumption reporting on company level in a retrospective way. Currently the reporting scheme is only for transparency purposes. At the last convention, the IMO expressed its intention to extend the regulation [3]. The extension should include fees for fuel consumption. An overview of the current regulation schemes is provided in Table 1. Although most regulations only apply to larger ships, smaller vessels currently being researched for autonomous shipping are also affected. In addition, larger ships will also benefit from autonomation and autonomy, even if there is still a long way to go.

Table 1. Regulation schemes [4, 3, 5]

Properties	IMO DCS	EU MRV (/UK MRV) EU ETS
Scope	International / global	Supranational, voyages from/to/within EU/UK
Reporting period	Year (retrospective)	Year (retrospective)
Timeline of tightening restrictions	Introducing a base target and surplus units in 2027	100% of emissions need to be included by 2026
Emissions concerned	CO_2	CO_2
Level	Company	Ship
Ships concerned	≥5,000 gross tonnage	≥5,000 gross tonnage (offshore and general cargo ships 400-5,000 GT included in EU MRV)
Figures to be reported	Annual aggregated data	Data per voyage, only voyages from or to EU
Allowed methods	Bunker Delivery Note; Bunker fuel tank monitoring; Flow meters	Bunker Delivery Note; Bunker fuel tank monitoring; Flow meters; Direct measurements

Next to IMO DCS and EU MRV / EU ETS there are additional local regulations that apply to locally restricted areas, e.g. harbours. Further the IMO is planning to introduce annual greenhouse gas fuel intensity (GFI) targets for ships. Ships that emitted emissions above the GFI target can balance their emission account buying the surplus of other ships on a trading market [3].

Additionally, the EU has introduced the EU Monitoring, Reporting and Verification (MRV) scheme, which requires more detailed reporting. The EU MRV come into force in 2018, also on a yearly and retrospective reporting basis. However, the reporting is on the ship level and considers only voyages starting and or ending in the EU. The Emission Trading System (ETS) of the EU

imposes not only technical challenges on ship owners, but also financial pressure. Starting 2026 100 % of the emissions need to be included in the reporting and paid for (opposed to 70 % in 2025) [6]. Depending on the current CO_2 prices and the route significant sums need to be paid, which underlines the need for exact and precise measurements and reporting. As the payment depends on the route an automated reporting system is beneficial.

2.1 Emission Determination Methods

To be compliant with regulations, the amount of carbon emissions emitted should be determined and reported. For emission determination, different data driven determination methods used for reporting tasks exist that are discussed. These methods can be divided into calculation-based and measurement-based methods. Calculation-based methods aim to determine fuel consumption and combine them with the emissions factors based on the fuel consumed. In contrast, measurement-based methods measure directly the emissions [5].

Calculation based methods:

1. Bunker Fuel Delivery Notes (BDN) are issued by the fuel suppliers and contain information about the supplied amount and the properties of the bunkered fuel [7]. To get the fuel consumed, the available fuel at the beginning is added and the available fuel at the end of the period subtracted [5]. Hence, fuel tank readings are also required.
2. Bunker Fuel Tank Monitoring on Board (BFTM) requires the monitoring of all fuel tanks on board the ship. Therefore, the fuel level of each tank is read [5].
3. Flow meters (FM) measure the fuel flow from the tanks to the consumers. The cumulation of all flows to consumers determines the fuel consumption of a ship [5].

Measurement based methods:

1. Direct CO_2 emissions measurement or Continuous Emission Measurement System (CEMS) is based on two elements to be combined. On the one side the measurement of the volumetric flow of the gas stream and on the other side the GHG concentration [5].

Considering the last three available reporting periods of the EU MRV, 2021 until 2023, the usage changes over time are analysed based on the chosen emission determination methods (Table 2). The methods could be used in parallel, respectively different methods for different time periods in the reporting period, meaning that the sum of all methods used can be higher than the sum of the ships reported. 2022 has a slight peak of the ships reported. However, the “Bunker Delivery Note (BDN) and period stock takes of fuel tanks (A)” is used most often over the years from 2021 to 2023 and had also a slight usage increase. Also, the “Bunker fuel tank monitoring on-board (B)” had a slight usage increase. The “Flow meters for applicable combustion processes (C)” the number of usages remains on the same level. The method “Direct CO_2 emissions measurement (D)” has only two entries in 2021, probably a test approach.

To categorise the determination methods, the advantages and disadvantages are briefly discussed regarding main requirements from the ship owners and the reporting institutions. For the decision makers it is important to get comparable and accurate results. The principle “A tonne must be a tonne” must be considered to ensure a fair allowances expenditure [8]. As ship owners are profit oriented companies, they have additionally considered the effort as well as the costs arising from the method application.

To be comparable, the regulations require the reporting of fuel consumption, which can be achieved by all methods. However, the methods differ in terms of accuracy. Hunsucker et al. measured the uncertainties of fuel consumption measurements for the BDN, BFTM and FM

Table 2. Overview of the emissions determination methods used in the EU MRV reporting (EU MRV THETIS CO_2 Emission reports [24])

Method used	2021	2022	2023
All entries/ Ships	12,485	13,476	12,733
Bunker Delivery Note (BDN) and period stock takes of fuel tanks (A)	5,981	6,766	6,418
Bunker fuel tank monitoring on-board (B)	3,767	3,845	4,098
Flow meters for applicable combustion processes (C)	4,259	4,589	4,279
Direct CO_2 emissions measurement (D)	2	0	0
Not filled (DoC not issued)	2	11	15

methods on different ships. The estimated overall uncertainty for the fuel consumption for BDNs is 3 %, 5 % for BFTMs and 8 %/10 % for FMs (depending on the fuel consumed) [7]. Mingjun et al. estimate the emission errors on +-5.5 % for BFTMs, +-3.1 % for FM and +-1 % for CEMS [8]. The gap between the two FM estimates can be attributed to the eight-year gap between them, during which technological advances and shifts in underlying assumptions occurred. All figures are still estimations due to missing ground-truth measurements, but they suggest accuracy gains from direct measurement. Calculation-based methods add uncertainty from variable fuel quality (e.g., heavy fuel oil). The EU MRV provides standard emission factors, and fuel quality should ideally be captured in BDNs, but these data are often disputed [9] because they affect price. In contrast, CEMS measures the gas stream's volumetric flow and GHG concentration (output) rather than inferring emissions from fuel type and consumption (input). Direct measurements of the output figures are considered to be more meaningful and accurate, since the actual emitted emissions are measured, rather than potential emitted emissions based on the input. Ultimately, the GHG emissions are of interest and not the fuel consumption itself. Nevertheless, the reduction of fuel consumption remains an optimisation parameter for ship owners and operators.

Even slight accuracy improvements can yield significant cost savings, assuming direct measurements report less emissions to be paid for than based on the calculations. For example, of all reported ships in the MRV THETIS dataset from 2023, the container ships are considered that have been at sea for more than two months or six months. Only these ships are considered as otherwise the relative effect for the ships would be negligible and would not be worth calculating. After 1,440 hours (two months) and 4,320 hours (six months) spent on sea, the average total amount of CO_2 emissions are 23,669 tonnes, respectively 27,113 tonnes [10]. Assuming an average carbon emission allowance price of 65 € for 2024 about [11], a shipowner would pay

€ 1.54 million and € 1.76 million in the near future. From 2026 onwards, all CO_2 emitted in the EU must be paid for. A 2 % reduction would save 30,800 and 35,200 € per year per ship.

The initial effort and costs for the BDNs are low, since they have already been issued. Nevertheless, the BDNs must be digitised, and the fuel consumption of each route determined which requires e.g. BFTM to determine the tank level at the beginning and the end of the routes. Verification requires cross checking, increasing effort and costs. Regarding BFTM, the tank soundings are routine work for the crew and add no additional effort. They can be conducted manually, leading to subsequent digitisation efforts, or with automatic measuring equipment installed in the tanks. Similarly, FMs also require measuring equipment to measure fuel consumption and the mapping of the fuel quality to the fuel consumed. The CEMS method is more costly, with effort similar to FM applications [12]. In summary, calculation-based methods cost less, while direct measurement is more accurate. If it yields lower reported emissions, large vessels facing high charges can realize substantial savings.

2.2 Digital reporting

As a solution to the obstacles for improving the energy efficiency of maritime vessels the need for comprehensive data collection is recognised [13]. Digitalisation is an important area in this field. However, digital solutions and big data applications for decarbonisation in the maritime environment such as environmental legislation monitoring are challenging [14]. An important challenge is the lack of available data in good quality to avoid failures [14, 15] such as incorrect reporting. Another challenge is the data integration of data from different collection systems, e.g. for the emission data, fuel consumption and engine data are required [14]. Standard management can help in this regard. The maritime industry lacks with standardisation for data collection system since the equipment manufacturers build “black box” applications which complicates development of applications that are based on different data sources. This is the case since these black box applications are not designed for interconnected systems. Standards are required [16] to enable data-driven solutions, facilitate data collection and processing and support real-time applications which allow deviations (e.g., unexpected overconsumption) to be detected and corrected immediately and pave the way to automated digital reporting.

2.3 State of the art

Various research projects have explored ways to measure or estimate CO_2 emissions from ships with greater accuracy. While this research addresses regulation compliance, real-time automation and/or direct measurements of emissions, none of it combines all these factors into one framework. The following presents relevant research, that combines at least two of these factors.

The need for more accurate data to understand which conditions enhance ships’ emissions in real world scenarios is recognised by Fan et al. [17]. They present a data-driven methodology for constructing typical operational conditions for ships, identifying three distinct operational conditions characterised by unique speed and engine parameters, demonstrating significant deviations from traditional static standards like ISO 8178-E3. In the same year, 2024 St. Pierre et al. presented a data-driven method for estimating ship’s engine fuel consumption in real-time. Their approach is tested and designed for tugboats [18]. In 2022 Zhou et al. proposed and tested a real-time measurement-modelling system for ship air pollution emission factors [19]. Their aim is to promote technical support for maritime law enforcement. Their system consists of three components: a portable exhaust monitoring device, an information platform, and a cloud server for data analysis and calculating emission factors. The system is designed to be applied in emission control areas and does not measure directly in the ships exhaust stream. In 2023 Wei et

al. aimed to use environmental data for routing decision support ensuring decarbonisation regulation compliance [20]. Therefore, they update their power estimation model to estimate the carbon emissions. They argue that the fuel consumption (key factor of carbon emission) is related to the power of a ship which can be estimated by resistance of the ship. The input for the power estimation model are the resistance models based on weather (wave height, …) and position data (AIS data, ...). Looking ahead, they state that sensor data could increase model accuracy. Li et al. presents a near real-time carbon accounting framework to determine the carbon emissions and enhance the decision making of the regulators. They include critical operational factors such as navigation data in the emission determination. For missing data, they use a prediction model. With this approach they overcome the retrospective approach [21] and pave the way for faster decisions regarding emission reduction measures with less effort.

The need for a more digitalised approach is recognised from regulatory point of view as well as from data collection point of view. As Chi et al. stated in 2017, the current literature focus on yearly emission/efficiency measures leading to the ignorance of dynamics in the emissions [22]. Looking at the reporting regulations, the focus is on the retrospective today. For real-time use cases data availability is the key issue. Since AIS data is available, they use it for dynamic information in combination with the static vessel characteristics. In a study published in 2024, Olaniyi et al. analyse the efficacy of maritime environmental regulations set by IMO, in addressing climate change challenges within the shipping industry [23]. The study points out complexities and gaps in current regulatory frameworks and emphasis the need for a more digitally enabled approach to enhance compliance and effectiveness of the regulations. As a reaction to EU regulation 2015/757 Capezza et al. presented a statistical framework for monitoring ship fuel consumption and CO_2 emissions. The authors highlight the inefficiencies of manual data acquisition and propose the use of multi-sensor navigation data for compliance. Although the study investigates ships in transit and not during port visits, the effectiveness of the approach was demonstrated in a case study [24]. The need for a high degree of digitalisation is also underlined by the findings of Rony et al., who conducted an online survey (74 participants) in 2017. The aim of the study was to identify the impact of MRV on maritime energy policies and examine issues with data quality in MRV implementation [25]. Their findings put emphasis on the importance of data quality, with human errors being the most significant cause of data inaccuracies, data integrity, as well as data management.

2.4 Research gap

Monitoring and reporting of emissions in shipping has continuously been more stringent and now incurs costs. Based on current decisions, it can be assumed that it will become even stricter in the future. Ship owners and operators must react to the upcoming challenges by choosing suitable emission determination methods to comply with the regulations. At the same time, they must reduce the reporting effort to remain competitive. This paper presents a framework that considers both aspects for regulatory compliancy. Direct measurement shows promising results in terms of improving accuracy and the associated cost savings potential. Calculation based methods lack e.g. due to non-standard fuels and aggregated default emission factors. Therefore, directly measuring the GHG emissions is promising for ship owners. Secondly, the framework focuses on an automated digitalised reporting workflow to reduce manual effort and avoid sources of error.

3. Automated Direct-Measurement Emissions Reporting

The conceptualised framework, shown in Figure 1, contains a workflow of ten building blocks, clustered into the four areas, namely data management, infrastructure, data quality and at the end the reporting. While the data management is executed on ship side, the assurance of data quality and the actual reporting is done on the landside. While steps 1, 7, 8, and 10 are still executed manually in part, the other steps are automated. The workflow is mirrored with a shipping company. In the following, the building blocks are described in more detail:

I. Data Management:

1. Within the *Data Collection* three different data sources are differentiated since they are handled slightly differently. The directly measured emission data (a) is collected from the sensors assembled in each of the ship's exhaust streams. For the determination of the GHG emissions, two values need to be measured, the volumetric flow and the volume concentration. In similar reporting applications, e.g. sulphur emission reporting, a data point is required at least every 285 seconds. In addition, further data is required to validate the

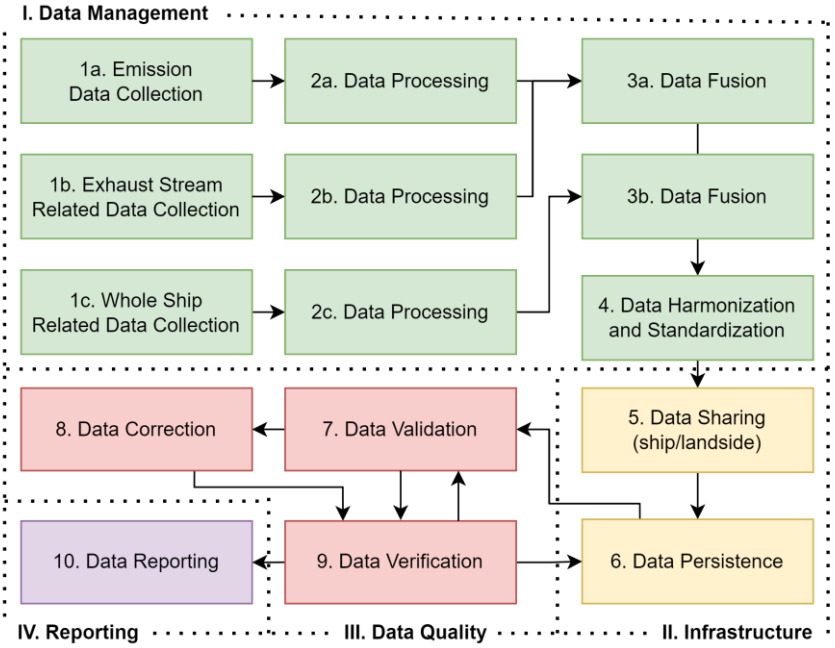

Figure 1. Reporting workflow based on directly measured emission data

measured values for later reporting, which were already recorded on the ship. Therefore, next to the direct emission measurements, exhaust stream related operation data (b) is collected. For example, fuel consumption, fuel oil type, and engine loads are relevant values for the validation. Each exhaust stream represents a consumer group of one or more consumers (e.g. the main engine and an auxiliary engine). In contrast, data related to the whole ship (c) such as the shipload, the speed, the weather and sea conditions are used for all consumer groups. This data (b, c) is requested from the ship's internal networks, e.g. by Modbus TCP, OPC UA and MQTT protocols. Since the framework is also to be used for partially

automated ships as retrofitting solution, manual data entry has to be possible, especially for "data relating to the whole ship" that does not originate entirely from the sensors.

2. To ensure a uniform and valid database for analysis and reporting, an automated *Data Processing* is done before. This is introduced as early as possible to avoid time-consuming error propagation for each data source separately. As required by ISO 19847, all collected data must be tagged with a timestamp to ensure consistency over time, if not already done by the former systems [26]. Sensor data can contain errors from various sources. Examples are noise, outliers, systematic errors, drifts and missing values [27]. Even if the most data are automatically collected, also manual collected (mainly in c) data is considered. Data entered manually may contain an extra digit or a reading error because you misread the line. If these errors are detected, for example by specifying minimum and maximum value for each data point before, they are handled e.g. by imputation [27] with the previous measured value. If too many values, e.g. all values of a day, are missing or indicate errors (the limit has to be set in advance), an alternative emission determination method must be used as a backup solution. A suitable alternative would be the BFTM, since the tank soundings are done regularly. Avoiding too many imputed values due to errors, these values must be tagged with their origin. Possible tags are "measured", "estimated" and "missing".
3. After processing, the *Data Fusion* combines the different data sources. This is done event driven, e.g. every 15 minutes the available data is fused as batch. Firstly (a), the emission data is combined with the exhaust stream related data, since they have the same scope. Therefore, the data assigned to the same consumers sets are merged. For example, data from the "consumer group 1" with "main engine" and "auxiliary engine 1" while "consumer group 2" contains "auxiliary engine 2" and "auxiliary engine 3". In contrast, the whole ship related data is not merged to each consumer group, as this would lead to data doublings, which would blow up the data messages shared with the landside. However, the datasets are tagged (b) with e.g. the ship number to enable a later fusion with the consumer groups. If more than one data point exists for the same e.g. sensor, the newer is taken as it is assumed to be correct. However, in general the whole time series is relevant not only the newest value.
4. As data differs from ship to ship and the systems used are developed as black box systems, *Data Harmonisation and Standardisation* is required. So far, the data has only been processed within their data source pools (e.g. consumer groups). Moreover, the different data sources are harmonised with each other to ensure consistent time formats and measurement units—this requires both time synchronization and unit normalization. Next, the data is transformed into a standard format with a unified naming. This enables a standardized analysis and validation workflow. For the standardisation, the VISTA set of standards and tools can be used which is based on ISO 19847 and ISO 19848 norms [28]. VISTA is not exclusively developed for emission reporting application cases but provides the possibilities to map emission data in a standard format and is also usable for application cases of other domains. Applying the standardisation, a ship specific data mapper is developed that maps the available ship data to the data points required by the emission reporting application. Data available in this format is used directly for verification and reporting purposes, as Det Norske Veritas uses this format and only one mapper needs to be developed for other verifiers. The basic functions are available as open source, enabling broad and cost-effective application.

II. Infrastructure:

5. Before the data is shared with the landside (*Data Sharing (landside)*), the data is cached to avoid data loss. If required by the verifier, long-term storage on board the ship is also

conceivable. As the connection at sea is not always stable and can be interrupted for several days, the data is shared continuously. This avoids multiple transfers in the event of multiple requests and ensures the availability of the newest available data [29]. However, to reduce communication costs, which are high in the maritime environment, it is suitable to create data batches, e.g. for one hour, and make use of loss free data compression methods. The use of suitable serialisation methods supports the reduction of message sizes [29]. This is required, since communication is more expensive at sea than on land.

6. On land, dynamic data is continuously persisted in a database (*Data Persistence*). As most data is time series data, time series-optimised databases are suitable. Static data, such as sensor specifications or exhaust stream geometries is stored in the database before and updated manual if required. To prevent unintended changes to data, it must be tamper-proof. Methods such as cyclic redundancy checking (CRC) are used for this purpose. Based on the stored data, the data reported to the authorities can be retraced if required and long-term analysis becomes possible. For the traceability use case it could be also required to store the data on board the ship.

III. Data Quality:

7. If new data is available on landside, *Data Validation* is triggered. This is an important step in the workflow to ensure the correctness of the reported data. For this step, the additional collected data (1b, 1c) is important. Since the effort should be kept to a minimum, a digital pre-validation is required. Therefore, any failures in the data must be identified and classified by algorithms according to their significance. In the validation, values out of area, drifts, correlations and metrics have to be determined and used to calculate the significance level. Introducing significance levels avoids overwhelming analysts with information. Based on the classification, the analyst, a human, can choose their own notification scheme. They are then regularly informed about the status of the collected data based on their own settings. In case of significant data discrepancies, a short reaction time is advisable to avoid consequential failures, e.g. if data is completely missing for an extended period or values showing a drift. Therefore, the reasons are investigated timely. If the algorithms are unable to find the failure sources, the analyst is required to find the failures, based on the information available. For humans, visual tools such as time series diagrams can support or a comparison with previous correct data or estimated data by a digital twin. The analyst's task is then to narrow down the cause of the error and estimate its significance. The corrections are saved and used for the learning of corrections to enable more autonomous system behaviour and to relieve the analyst. In the case of no deviations, multiple notifications can be grouped together and sent e.g. in a weekly or monthly rhythm.
8. Based on the error localisation, the data is corrected (*Data Correction)*. Possible measures to correct the error are re-measuring if not too much time has passed or making a suitable estimation based on previous or subsequent values. For some errors, such as typos where an extra digit has been entered, the corrective measures are obvious. For traceability purposes, it is important to store a brief correction notice. At this point, it is worth mentioning that errors should not only be corrected to make the system satisfactory. To prevent this behaviour, there is an option provided to not correct diverging values that can be explained, or where correction is not possible, with a short notice. For example, if the sensor system fails and no correction is possible, the use of a chosen backup determination method is advised.
9. However, if the data is already correct (which should be the standard case) or the data is corrected, the data is sent to the reviewer/verifier for *Data Verification*. Before sending the

data to the verifier, based on the emissions, fuel consumptions are calculated as they are subject of reporting. Additionally, the data is filtered to avoid releasing too much information that constitutes trade secrets and should not be disclosed to third parties. As required by the EU MRV reporting, the measurements for the concentration and the flow rate are aggregated for each source separately to hourly averages. since it is required for direct measurement [5]. In case of consistent data, the data is verified by the verifier. If this is not the case, the verifier sends the data back and the data is validated again and corrected.

IV. Reporting:

10. After the reporting period (yearly basis), the data is reported as a whole set (Data Reporting). Therefore, the verified data is e.g. entered into the emission report (in case of the EU MRV) and sent to the responsible institutions.

4. Discussion

The presented framework takes a modular approach to collecting data efficiently, harmonising and standardising it, and reporting the required fuel consumption data to the relevant authorities. The combination of direct measurements and digitalisation improves accuracy and reduces manual effort. In terms of improving accuracy direct measurements allow aggregated emission factors to be omitted. This enables the consideration of real time influences on emissions and understanding of measures on emissions directly. As for the digitalisation of the reporting workflow next to the effort reduction, a data cleaning and standardisation approach was presented that enables interoperability with the verifiers and the use of data for further applications. By cleaning the data early on, effortful, more time-consuming cleanings later on are prevented. Additionally, the modular approach can be more easily implemented on different ships because in the standard case only the first modules need to be adapted. The others are already set up on standardised data. The modular approach also makes it possible to continuously replace partially manual steps with fully automated ones based on the experience gained after implementation and the data required for automation, for example to derive corrections. However, since sensor systems can fail a backup system is still required which leads to additional effort. In the standard cases, e.g. tank soundings are routine tasks for the crew that must be carried out anyway, so that there is little or no additional work involved. Beyond technical considerations, organisational questions must be clarified, specifically who will be responsible for data analysis and which tasks can be fully automated assuming the digital algorithms perform reliably.

Digitising more and more steps on board of ships paves the way to autonomy or partly autonomous operations. The presented framework is easily retrofittable and thus suited for autonomous and non-autonomous ships. In practical terms, this approach also offers cost benefits. Greater accuracy leads to more precise carbon emissions, so costs can be saved quickly as shown in the exemplary calculation in section 2.1. Due to the high sums involved, it turns out there is significant potential for savings. Based on the current regulations, other GHG emissions will be soon included, and the allowance price should rise, further increasing the savings potential.

5. Conclusion and Outlook

Finally, this paper addressed the growing challenge posed by stricter GHG-monitoring requirements in shipping. Therefore, an end-to-end framework consisting of ten building blocks

that start with the data collection and end up in the reporting is proposed. Due to its modular architecture, the framework can be seamlessly deployed on both (partly) autonomous and existing vessels, with the latter being retrofitted to meet emissions reporting standards. It combines direct emissions measurement with a fully digitalised reporting workflow, enabling accuracy improvement and manual effort reduction. This is achieved by considering the various data sources required for emission reporting and validation, and by cleaning the data to map it in a standardized format (e.g. via VISTA/ISO norms). By integrating tamper-resistant safeguards into its semi-automated validation and correction loops, which can be fully automated as more data becomes available, the system ensures data integrity and fosters trust. Thanks to the integrated approach, time-consuming data searches are avoided while errors are minimised. A simple analysis of the initial costs shows that even minor improvements in accuracy lead to significant savings in allowance fees, which will increase in the coming years.

Future work will focus on implementing the framework on board a container ship and evaluating it. The evaluation must consider the accuracy of the direct measurement approach, as well as the effort involved, to produce a cost calculation. Applications for emission estimation using digital twins are also useful because they can be used for validation through the automatic detection and correction of anomalies. Digital twins can also be used to bridge short periods of missing data. Furthermore, it should be considered how the data can be reused and shared to increase the benefit of the data. One possibility is to use the data for route optimisation or to share it with interested parties, such as charterers or port authorities. For the latter use case, data spaces could facilitate data sharing.

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