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Ships and marine technology — Measurement of changes in hull and propeller performance —

Part 1: General principles

Navires et technologie maritime — Mesurage de la variation de performance de la coque et de l'hélice —

Partie 1: Principes généraux

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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

The committee responsible for this document is ISO/TC 8, *Ships and marine technology*, Subcommittee SC 2, *Marine environment protection*.

A list of all parts in the ISO 19030 series can be found on the ISO website.

Introduction

Hull and propeller performance refers to the relationship between the condition of a ship's underwater hull and propeller and the power required to move the ship through water at a given speed. Measurement of changes in ship specific hull and propeller performance over time makes it possible to indicate the impact of hull and propeller maintenance, repair and retrofit activities on the overall energy efficiency of the ship in question.

The aim of the ISO 19030 series is to prescribe practical methods for measuring changes in ship specific hull and propeller performance and to define a set of relevant performance indicators for hull and propeller maintenance, repair and retrofit activities. The methods are not intended for comparing the performance of ships of different types and sizes (including sister ships) nor to be used in a regulatory framework.

The ISO 19030 series consists of three parts.

— ISO 19030-1 outlines general principles for how to measure changes in hull and propeller performance and defines a set of performance indicators for hull and propeller maintenance, repair and retrofit activities.

— ISO 19030-2 defines the default method for measuring changes in hull and propeller performance and for calculating the performance indicators. It also provides guidance on the expected accuracy of each performance indicator.

— ISO 19030-3 outlines alternatives to the default method. Some will result in lower overall accuracy but increase applicability of the standard. Others may result in same or higher overall accuracy but include elements which are not yet broadly used in commercial shipping.

The general principles outlined, and methods defined, in the ISO 19030 series are based on measurement equipment, information, procedures and methodologies which are generally available and internationally recognized.

Ships and marine technology — Measurement of changes in hull and propeller performance —

Part 1: General principles

1 Scope

This document outlines general principles for the measurement of changes in hull and propeller performance and defines a set of performance indicators for hull and propeller maintenance, repair and retrofit activities.

The general principles outlined and performance indicators defined are applicable to all ship types driven by conventional fixed pitch propellers, where the objective is to compare the hull and propeller performance of the same ship to itself over time.

NOTE Support for additional configurations (e.g. variable pitch propellers) will, if justified, be included in later revisions of this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
hull and propeller performance
relationship between the condition of a ship's underwater hull and propeller and the power required to move the ship through water at a given speed

3.2
delivered power
P_D
power delivered to the propeller (propeller power)

3.3
speed through the water
V
ship's speed through water for a given set of service (environmental) and loading (displacement/trim) conditions

3.4
accuracy
described by trueness and precision, where trueness refers to the closeness of the mean of the measurement results to the actual (true) value and precision refers to the closeness of agreement within individual results

Note 1 to entry: See ISO 5725-1:1994, 3.6 and Introduction 0.1.

3.5
uncertainty
probability that the measurement of a quantity is within the specified accuracy to that quantity's actual (true) value

3.6
filtering
method of removing unwanted data

3.7
normalization
refers to the creation of shifted and scaled versions of statistics, where the intention is that these normalized values allow the comparison of corresponding normalized values in a way that eliminates the effects of specific influences

3.8
performance indicators
PIs
used to evaluate the effectiveness of, or to trigger, a particular activity

3.9
dry-docking
bringing the ship onto dry land to maintain, repair and/or retrofit the parts of the hull that are submerged while the ship is in service

3.10
out-docking
period immediately following a dry-docking

3.11
dry-docking interval
period between two consecutive dry-dockings

4 General principles

4.1 Hull and propeller performance

Hull and propeller performance refers to the relationship between the condition of a ship's underwater hull and propeller and the power required to move the ship through water at a given speed. Hull and propeller performance is related to variations in power, because ship hull resistance and propeller efficiency are not directly measurable quantities.

4.2 Ship propulsion efficiency and total resistance

Hull and propeller performance is closely linked to the concepts of ship propulsion efficiency and ship resistance. The performance model is based on the relation between the delivered power and the total resistance where delivered power, P_D, can be expressed as Formula (1):

$$P_D = \frac{R_T \times V}{\eta_Q} \tag{1}$$

where

R_T is the total in-service resistance (N);

V is the ship speed through water (m/s);

η_Q is the quasi-propulsive efficiency (-).

The total resistance consists of several resistance parts and can be written as Formula (2):

$$R_T = R_{SW} + R_{AA} + R_{AW} + R_{AH} \tag{2}$$

where

R_{SW} is the still-water resistance (N);

R_{AA} is the added resistance due to wind (N);

R_{AW} is the added resistance due to waves (N);

R_{AH} is the added resistance due to changes in hull condition (fouling, mechanical damages, bulging, paint film blistering, paint detachment, etc.), (N).

Likewise, the quasi-propulsive efficiency consists of different efficiency components expressed as Formula (3):

$$\eta_Q = \eta_0 \eta_H \eta_R \tag{3}$$

where

η_0 is the open-water propeller efficiency;

η_H is the hull efficiency;

η_R is the relative rotative efficiency.

The added resistance due to changes in hull condition can be expressed as Formula (4):

$$R_{AH} = \frac{P_D \times \eta_Q}{V} - (R_{SW} + R_{AA} + R_{AW}) \tag{4}$$

where

- V is the ship speed through water, can be measured directly;
- P_D is the delivered power, must be approximated – for example based on calculations of shaft power;
- P_S is from measurements of shaft torque and shaft revolutions or, alternatively, from calculations of brake power;
- P_B is from SFOC reference curves, measurements of fuel flow and temperature and data on calorific value, density and density change rate for the fuel being consumed.

Variations in the delivered power required to move the ship through water at a given speed, and the same environmental conditions and operational profile, are due to changes in the underwater hull resistance and/or propeller efficiency. Changes in underwater hull resistance are due to alterations in the condition of the hull. Changes in the propeller efficiency are due to both alterations in the condition of the propeller and to modifications to the flow of water to the propeller (the hull wake) as consequence of alterations to the hull condition.

For a vessel in service, both environmental conditions and operational profile (e.g. speed, loading, trim) vary. In order to measure changes in the speed-power relationship for a vessel in service, it is necessary to compare two periods (a reference period and an evaluation period) where the environmental conditions and the operational profile are adequately comparable (filter the observed data) and/or apply corrections (normalize the observed data).

There are a number of alternative procedures for filtering and normalizing observed data. These procedures each have advantages and disadvantages in terms of the resulting accuracy of the measurements. This document prescribes a practical blend of filtering and normalization procedures found to yield sufficient accuracy.

NOTE The relative importance of the different resistance components varies to certain degree with the operational and environmental condition the vessel is exposed to. Also, the accuracy of the models to correct/normalize for such variations depends on the operational and environmental conditions. These dependencies impact the accuracy of the hull and propeller performance indicators as described in the current standard. Therefore, in the estimation of the accuracy of the performance indicators and for the intended use comparable operational and environmental conditions over the reference and evaluation period (see Annex A) are assumed. Future revisions of this document will re-evaluate if more accurate correction formulae are available that take the above mentioned dependencies into consideration.

Hull and propeller maintenance, repair and retrofit activities have an effect on the energy efficiency of a ship in service. An indication of these effects can be obtained by measurement of changes in the delivered power required to move the ship through water at a given speed between two periods for which the environmental conditions and operational profiles have been made adequately comparable through filtering and/or normalization of the observed data.

4.3 Primary parameters when measuring changes in hull and propeller performance

The above definition gives ship's speed through the water and delivered power as the two primary parameters when measuring changes in hull and propeller performance.

NOTE If hull performance is to be separated from propeller efficiency, propeller thrust would also have to be measured.

For these parameters, different measurement approaches, and for each approach, different sensors with different signal qualities are available. In ISO 19030-2, default measurement approaches and associated "minimum required" signal quality values are specified.

If sensors with the minimum required signal quality are not available, alternative measurement approaches can be used, but they introduce additional uncertainty. In ISO 19030-3, alternative measurement procedures are described. For each alternative, the minimum required signal quality is specified together with an estimation of the additional uncertainty introduced.

4.4 Secondary parameters

In order to apply the filtering and normalization procedures necessary to make the reference period and evaluation period adequately comparable, measurements of both the environmental conditions and the ship's operational profile are required. Relevant environmental factors are as follows:

— wind speed and direction;

— significant wave height, direction and spectrum;

— swell height, direction and spectrum;

— water depth;

— water temperature and density.

Relevant operational factors are as follows:

— speed;

— loading conditions (static draught, static trim, heel);

— dynamic floating conditions (motions, dynamic draught, dynamic trim);

— rudder angle / frequency of rudder movements.

If reliable sensor signals are not available for all parameters, either signals from alternative sensors can be used to approximate and/or for practical purposes one must assume their effects "average out over time". Using alternative sensors or relying on an equal distribution assumption introduces additional uncertainty.

In ISO 19030-2, a "minimum set" of sensor signals and the "minimum required" signal quality for each sensor are specified for the default method for measuring changes in hull and propeller performance.

In ISO 19030-3, alternative sets of sensor signals and "minimum required" signal quality are defined, together with estimations of their effect on the expected accuracy of the performance indicators.

4.5 Measurement procedures

4.5.1 General

There are three basic procedural steps involved when measuring changes in hull and propeller performance. Figure 1 summarizes these three steps.

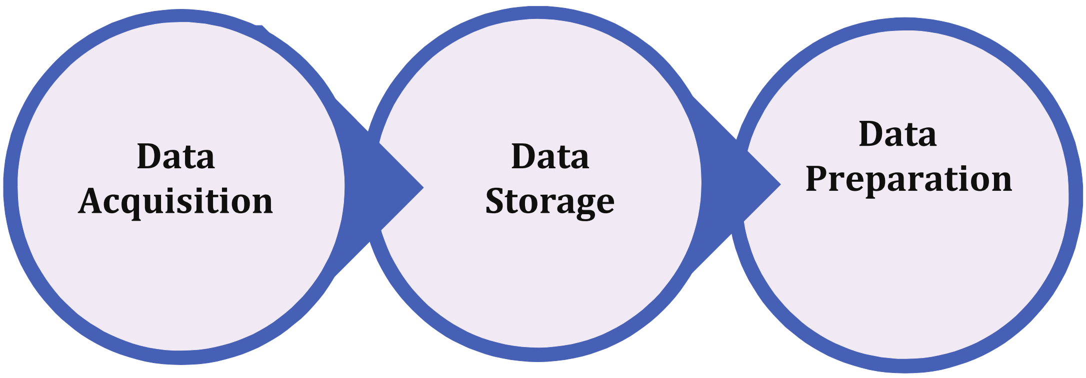


Figure 1 — Procedural steps when measuring changes in hull and propeller performance

The accuracy of a measurement is determined by both its trueness and its precision (see ISO 5725). Trueness refers to the closeness of the mean of the measurement results to the actual (true) value. Precision refers to the closeness of agreement within individual results and is a function of both repeatability and reproducibility. Reproducibility refers to the variation arising using the same measurement process among different instruments and operators, and over longer time periods. Measurement procedures have a considerable impact on the reproducibility of, and therefore on the accuracy of, the performance indicators.

NOTE The procedural steps do not have to be conducted in the above sequence. For example, some preparation of the data can be done as a part of data acquisition.

4.5.2 Data acquisition

Data acquisition refers to the systematic process of recording (manually and/or automatically) signals/data from the relevant sensors, equipment installed on the vessel and external information providers. Manual data collection is typically performed once every day (noon data). Generally, automated data collection occurs at a much higher frequency.

4.5.3 Data storage

Data storage refers to the saving and retention of collected data in a suitable format. This process should allow previously stored data to be kept together with new data, and ordering it in a sequence so that it is easy to retrieve when required.

4.5.4 Data preparation

Data preparation includes extracting, compiling, screening and validating the data to give it a structure, format and quality suitable for further processing. A set of non-dimensional performance values, that reflect the changes in the hull and propeller performance over the given period of time, are then calculated. Different sub-sets of the performance values are used to calculate the various performance indicators. Data preparation can be partially or fully automated.

Practical approaches to data acquisition, data storage and data preparation that yields a high expected accuracy is defined in ISO 19030-2, the default method for measuring changes in hull and propeller performance.

In ISO 19030-3, alternatives to the measurement procedures are defined and the impacts on the expected accuracy of the performance indicators are described.

5 Performance indicators

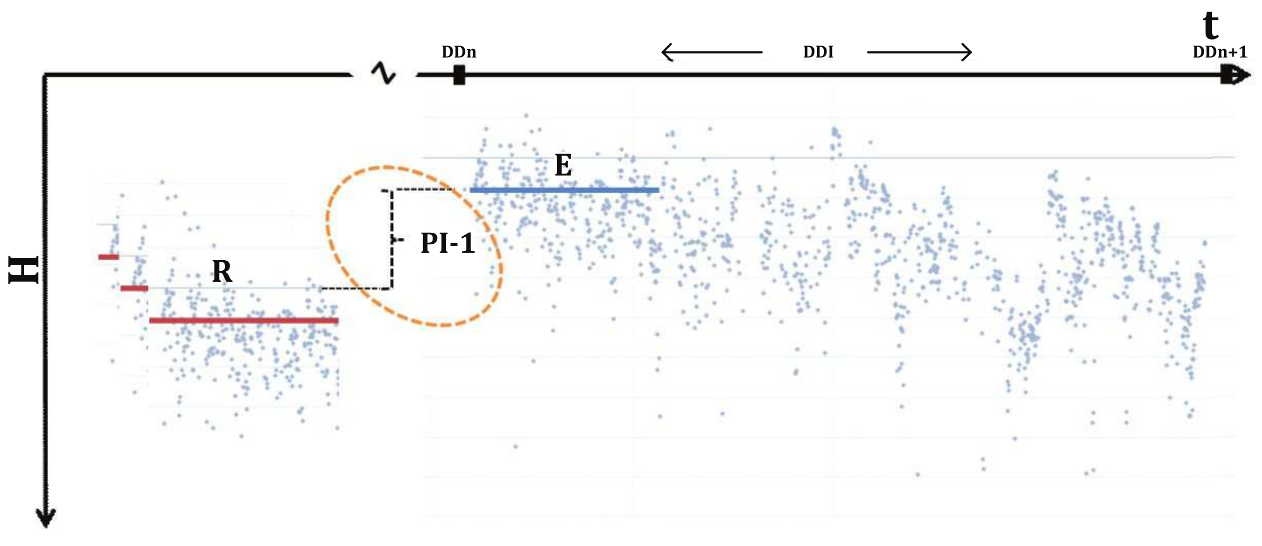
Measurements of ship specific changes in hull and propeller performance can be used in a number of relevant performance indicators to determine the effectiveness of hull and propeller maintenance, repair and retrofit activities. Table 1 outlines four basic hull and propeller performance indicators.

Table 1 — Basic hull and propeller performance indicators (PIs)

Performance indicator	Definition
Dry-docking performance: Determining the effectiveness of the dry-docking (repair and/or retrofit activities)	Change in hull and propeller performance following present out-docking (evaluation period) as compared with the average from previous out-dockings (reference periods).
In-service performance: Determine the effectiveness of the underwater hull and propeller solution (including any maintenance activities that have occurred over the course of the full dry-docking interval)	The average change in hull and propeller performance from a period following out-docking (Reference period) to the end of the dry-docking interval (evaluation period).
Maintenance trigger: Trigger underwater hull and propeller maintenance, including propeller and/or hull inspection	Change in hull and propeller performance from the start of the dry-docking interval (Reference period) to a moving average at any chosen time (evaluation period).
Maintenance effect: Determine the effectiveness of a specific maintenance event, including any propeller and/or hull cleaning	Change in hull and propeller performance measured before (Reference period) and after (evaluation period) a maintenance event.

5.1 Dry-docking performance: Change in hull and propeller performance following present out-docking as compared with the average from previous out-dockings

The change in hull and propeller performance following present out-docking as compared with the average from previous out-dockings (where data/measurements are available) is useful for determining the effectiveness of the dry-docking.



Key

H hull and propeller performance
t time
DDn present dry-docking
DDn+1 next dry-docking
DDI dry-docking interval
R reference period: average hull and propeller performance following previous out-dockings
E evaluation period: hull and propeller performance following present out-docking
PI-1 performance indicator 1: dry-docking performance

Figure 2 — Dry docking performance

During a dry-docking, the propeller(s) are typically cleaned, polished and/or repaired and the underwater hull is typically cleaned, spot or fully blasted, repaired and re-coated. In addition, retrofits may be undertaken to improve the performance of the hull, propeller or both.

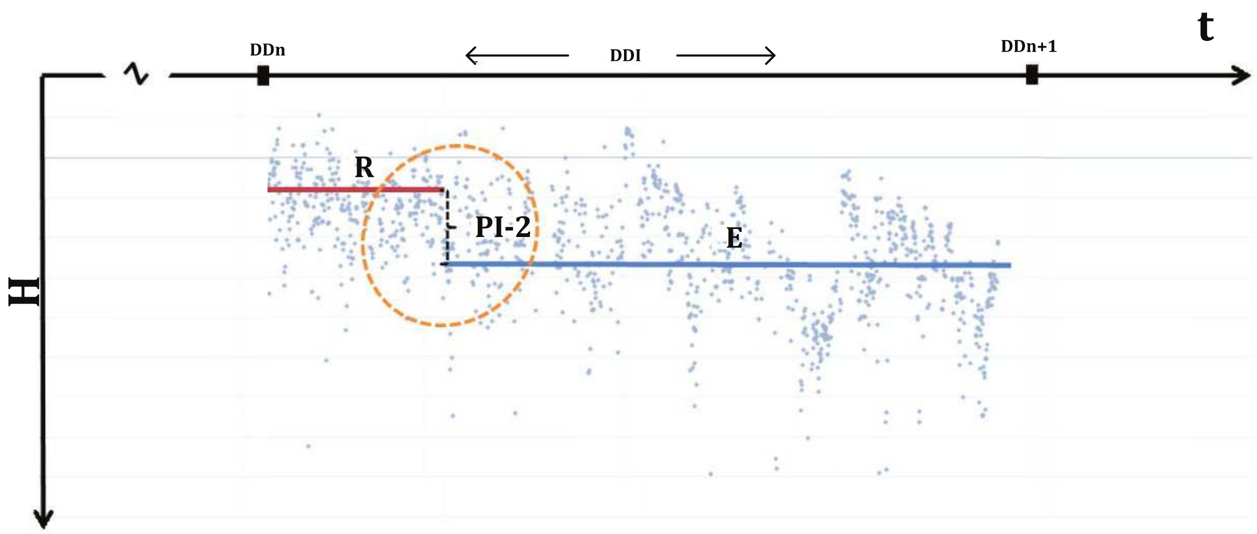
It is not possible to accurately isolate individual effects (for example impact of differences in level or quality of pre-treatment, quality of application or surface characteristics of paint). But, if only a sub-set of effects are expected to differ between the dry-dockings and everything else can reasonably be assumed to be the same, the performance indicator can serve as an indicator for this sub-set of effects.

The procedures for calculating this performance indicator are provided in ISO 19030-2 and ISO 19030-3.

NOTE Damage to, and deformation of, the hull occurring during the dry-docking, for example, bulging caused by improper placement of supporting blocks, will affect measured hull and propeller performance and, unless accounted for, is a source of uncertainty in this performance indicator.

5.2 In-service performance: The average change in hull and propeller performance over the period following out-docking to the end of the dry-docking interval

The average change in measured hull and propeller performance over the period from the out-docking to the end of the dry docking interval can be used to determine the effectiveness of the underwater hull and propeller solutions including hull coatings used and any maintenance activities that have occurred over the course of the dry-docking interval.



Key

H	hull and propeller performance
t	time
DDn	present dry-docking (or in the case of a new ship, date of entry into service)
DDn+1	next dry-docking
DDI	dry-docking interval
R	reference period: hull and propeller performance following present out-docking
E	evaluation period: avg. hull and propeller performance over remainder of dry-docking interval
PI-2	performance indicator 2: in-service performance

Figure 3 — In-service performance

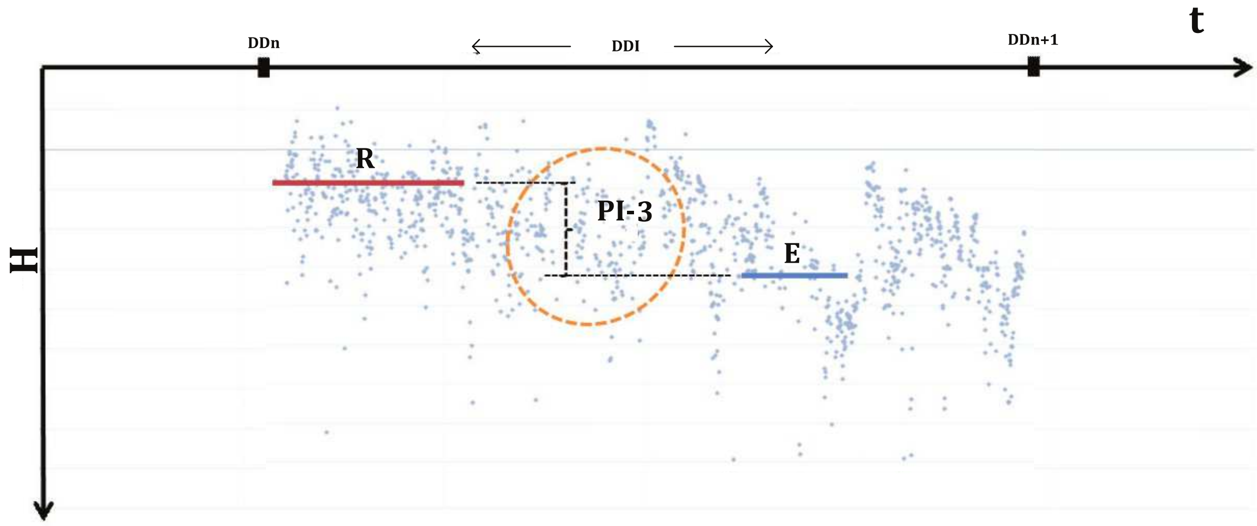
The procedures for calculating this performance indicator are provided in ISO 19030-2 and ISO 19030-3.

NOTE 1 Damage to, and deformation of, the hull occurring during the dry-docking, for example bulging caused by improper placement of supporting blocks, will affect measured hull and propeller performance and, unless accounted for, is a source of uncertainty in this performance indicator.

NOTE 2 Fouling of the propeller(s) (and / or tip damage) can have a significant influence on hull and propeller performance. If an indication of the change in hull performance is required in isolation, it is necessary that the propeller(s) be clean and un-damaged during both reference and evaluation periods.

5.3 Maintenance trigger: Change in hull and propeller performance from the start of the dry-docking interval to a moving average at any chosen time

The measured change in hull and propeller performance from the start of the dry-docking interval to a moving average at a chosen time during the same interval can be used as a trigger for underwater hull and propeller maintenance, including propeller and/or hull cleaning.



Key

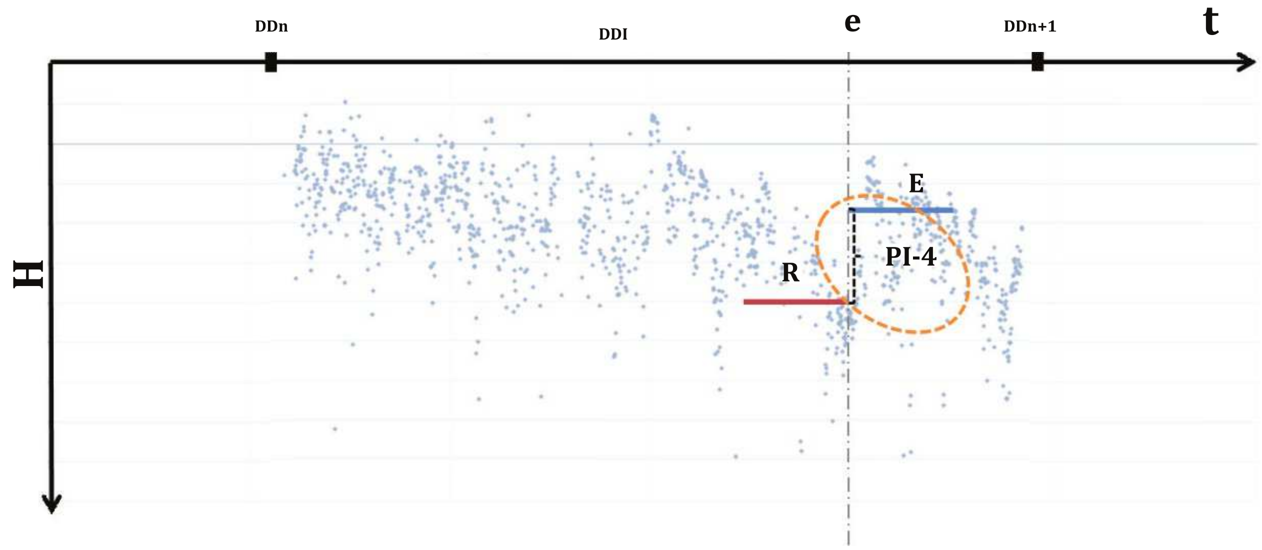
H	hull and propeller performance
t	time
DDn	present dry-docking (or in the case of a new ship, date of entry into service)
DDn+1	next dry-docking
DDI	dry-docking interval
R	reference period: hull and propeller performance following present out-docking
E	evaluation period: moving average hull and propeller performance at any chosen time
PI-3	performance indicator 3: maintenance trigger

Figure 4 — Maintenance trigger

The procedures for calculating this performance indicator are provided in ISO 19030-2 and ISO 19030-3.

5.4 Maintenance effect: Change in hull and propeller performance measured before and after a maintenance event

The change in hull and propeller performance measured before and after a maintenance event can be used to determine the effectiveness of a specific maintenance activity that has taken place in the interval between the measurements, including any propeller and/or hull cleaning.



Key

H	hull and propeller performance
t	time
DDn	present dry-docking (or in the case of a new ship, date of entry into service)
DDn+1	next dry-docking
DDI	dry-docking interval
e	maintenance event
R	reference period: hull and propeller performance before maintenance event
E	evaluation period: hull and propeller performance after maintenance event

Figure 5 — Maintenance effect

The procedures for calculating this performance indicator are provided in ISO 19030-2 and ISO 19030-3.

6 Measurement uncertainties and the accuracy of the performance indicators

Consistent with ISO 5725-1, important sources of uncertainty, that influence the accuracy of the performance indicators, include the following:

— measurement uncertainty (e.g. related to a sensor’s accuracy, both the uncertainty that might be observed in a laboratory test in ideal conditions and any additional uncertainty that might be related to a sensor’s installation, maintenance and operation);

— uncertainty introduced through the use of a sample, an average, or aggregate, value of a parameter when that parameter is variable with time (e.g. using an average of the wind speed over a period of time);

— uncertainty introduced through the use of formulas which necessarily simplify relationships in order to manage the complexity, or because of imperfect information (e.g. use of sea trial data for draught corrections, or the approximation in the Admiralty formula if used to normalize data measured at a specific draught to a reference draught).

The aim of this document is to define standard procedures for the determination of performance indicators such that:

— the uncertainties described above are at levels that enable the meaningful deployment of the performance indicators for a variety of decision making applications (recognizing that not all methods may be appropriate for all applications);

— all three of the uncertainties are reduced by as much as is practicable, given different availabilities of sensors and hardware and the requirement that an ISO standard be transparent;

— the relative accuracies resulting from method differences and variations in ISO 19030-2 and ISO 19030-3 are made transparent.

Appropriate use of the performance indicators for decision-making purposes is dependent on understanding to what extent uncertainty influences the accuracy of each.

For the default method, guidance on the expected accuracy of each performance indicator is therefore provided in ISO 19030-2 and ISO 19030-3. Similarly, for the alternatives to the default method, guidance on their impact on the expected accuracy of the performance indicators is provided in ISO 19030-3.

The framework used to assess the expected accuracies is described in Annex A.

Annex A
(informative)

Method and assumptions for estimating the uncertainty of a performance analyses process

A.1 General

The aim of an uncertainty analysis is to describe the range of potential outputs of the system at some probability level, or to estimate the probability that the output will exceed a specific thresholds or performance measure target value[16].

The existing literature relevant to uncertainty quantification within the shipping industry is found most notably in the ITTC recommended procedures. This includes established methods for estimating the uncertainty in experimental results relating to hydrodynamic experiments[12], for example, in propulsion open water tests [11] and resistance tests [12]. Applications of these are shown in Reference [15] in relation to towing tank tests and in Reference [10] in relation to sea trials. These methods are based on the ISO "Guide to Uncertainty in Measurement"[14] and the AIAA standard on the assessment of experimental uncertainty[2]. A key document, used as the main source to formulate the method described in this annex, is the "Guide to the expression of uncertainty in measurement"[14] which provides a procedure adopted by many bodies[6]. Reference [5] provides derivation and discussion of the method and procedures.

A.2 Uncertainty analysis methods overview, selection

The GUM framework is itself derived in part from the work of Coleman (1990) who introduced for the first time the balanced treatment of precision and bias errors, they also describe a method to treat correlated errors and small sample sizes. The nomenclature and definitions of Coleman and Steele are consistent with those of the ANSI/ASME standard on Measurement Uncertainty; precision error is the random component of the total error, sometimes called the repeatability error, it will have a different value for each measurement, it may arise from unpredictable or stochastic temporal and spatial variations of influence quantities, they are due to limitations in the repeatability of the measurement system and to facility and environmental effects. The bias error does not contribute to scatter in the data but is the fixed, systematic or constant component of the total error; it is the same for each measurement.

The basic premise of the GUM framework is twofold; firstly, to characterize the quality of the output in terms of the systematic and random errors which are then combined to obtain the overall uncertainty in a probabilistic basis and secondly, it includes representation of how well one believes they know the true value of the measurand, quantified in terms of probabilities that express degrees of belief. This is a refinement to traditional error analysis in which the output is in terms of a best estimate plus systematic and random error values.

This leads to the classification of uncertainties according to the method used to evaluate them; type A evaluation of uncertainties is based on statistical methods or repeated indication values, i.e. Gaussian distributions derived from observed frequency distributions. Type B evaluation of uncertainties is based on scientific judgment (any basis other than statistical), this is *a priori* distribution based on a degree of belief, a feature of Bayesian inference, if there is no specific knowledge one can only assume a uniform or rectangular distribution of probabilities to be assigned. In accordance with the second premise, both types of evaluation are based on probability distributions (quantified by variances and standard distributions) and the classification is not to indicate differences in the nature of the components.

The GUM specifies three methods of propagation of distributions:

a) the GUM uncertainty framework, constituting the application of the law of propagation of uncertainty;

b) Monte Carlo (MC) methods;

c) analytical methods.

The analytical method c) gives accurate results involving no approximations; however, it is only valid in the simplest of cases while both methods a) and b) involve approximations. The GUM framework is valid if the model is linearized and the input pdfs are Gaussian, this is the framework followed by the AIAA guidelines[2] and the ITTC guide to uncertainty in hydrodynamic experiments[12], of which relevant examples include applications to water jet propulsion tests[13] and resistance experiments[12][15]. In these examples, sensor measurement repeatabilities (same conditions, equipment, operator and location) are identified as precision limits for each variable and are described by a distribution function or simply by a standard deviation[4]. The bias limit for each elemental input may be present as a fixed (mean value) or as a random variable, in the latter case it would be defined by the band within which you can be 95 % confident that the true value lies[2], i.e. the band in which the (biased) mean result, would fall 95 % of the time if the experiment were repeated any times under the same conditions using the same equipment.

If the assumptions of model linearity and Gaussian input pdfs are violated or if these conditions are questionable then the MC method can generally be expected to lead to a valid uncertainty statement. In the probabilistic risk assessment field, Monte Carlo Analysis is perhaps the most widely used probabilistic method[7], relevant examples in the shipping industry include applications in sea trial uncertainty analysis[10]. A further advantage of the MC method is that the input uncertainties are based on probability distributions (rather than associating standard uncertainties with estimates of each input) therefore separation of the inputs into type A and type B is not necessary, finally, a more insightful numerical representation of the output is obtained and is not restricted to a Gaussian pdf.

Because the model of ship performance is non-linear and there is no extensive evidence that both input and output uncertainties can be represented as Gaussian pdfs, the MC method is selected for the purpose of estimating the uncertainty of the methods described in ISO 19030-2 and ISO 19030-3. This method also enables robust, experimental investigation of the sensitivity of the overall uncertainty to changes in the input uncertainties. Observing the sensitivities enables the justification of assumptions regarding which inputs can be safely assumed to have negligible influence on the outcome.

A.3 Method description

This work adopts the following approach:

a) identify each elemental uncertainty source, classify, define probability distribution parameters;

b) simulate the ship's operating profile and performance trend, and representation of data acquisition, sampling and filtering;

c) propagate the errors through the model and simulation using the Monte Carlo method and defined probability distributions for key sources of uncertainty [from step a)];

d) formulate the output distribution of the result, report overall uncertainty.

The details associated with these steps are also shown diagrammatically in Figure A.1.

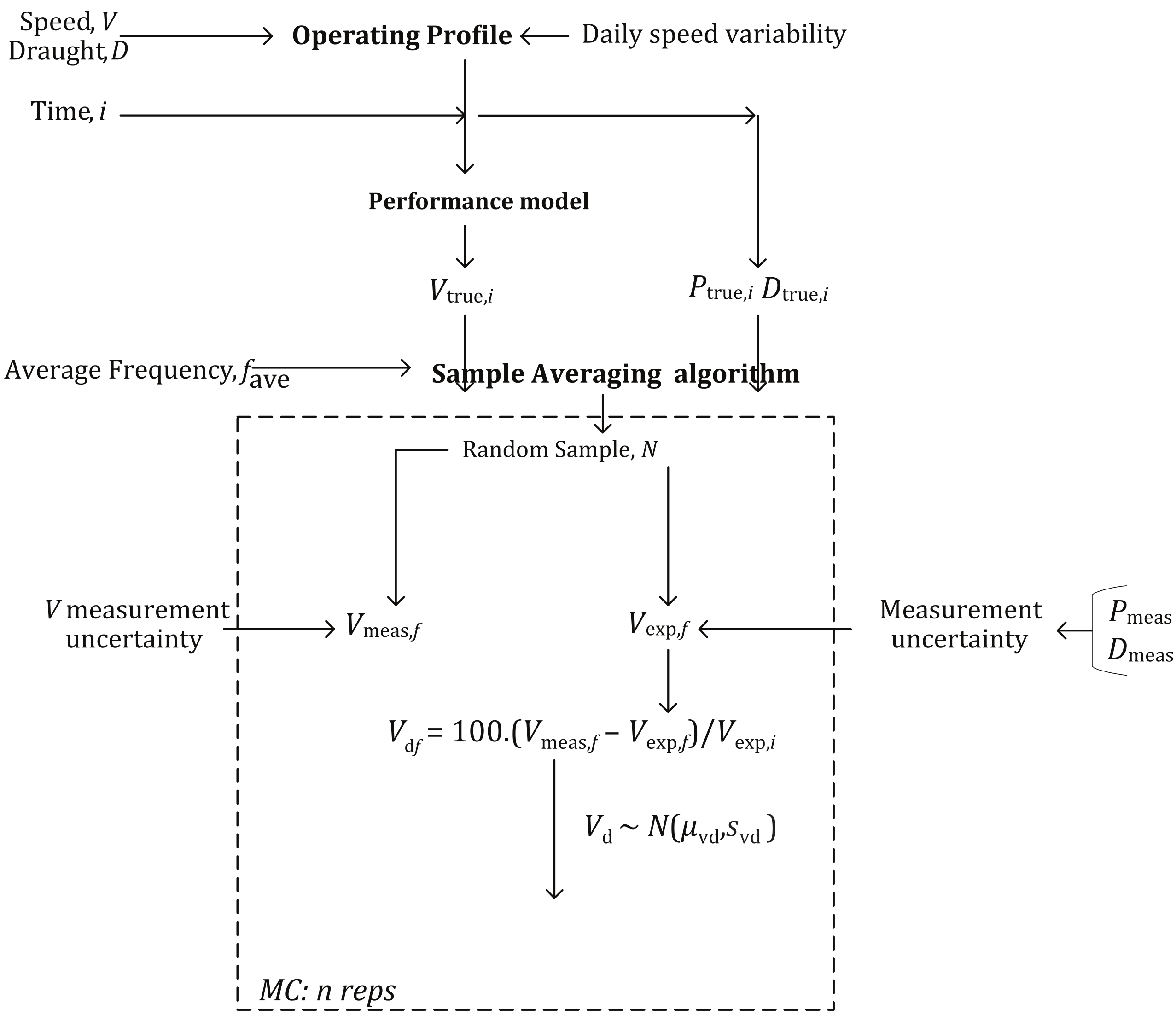


Figure A.1 — Diagrammatic presentation of the simulation method employed to derive estimates of performance value uncertainty

A.4 Sources of uncertainty in ship performance monitoring

A.4.1 General

A number of sources of uncertainty in the performance indicator are identified in Figure A.2.

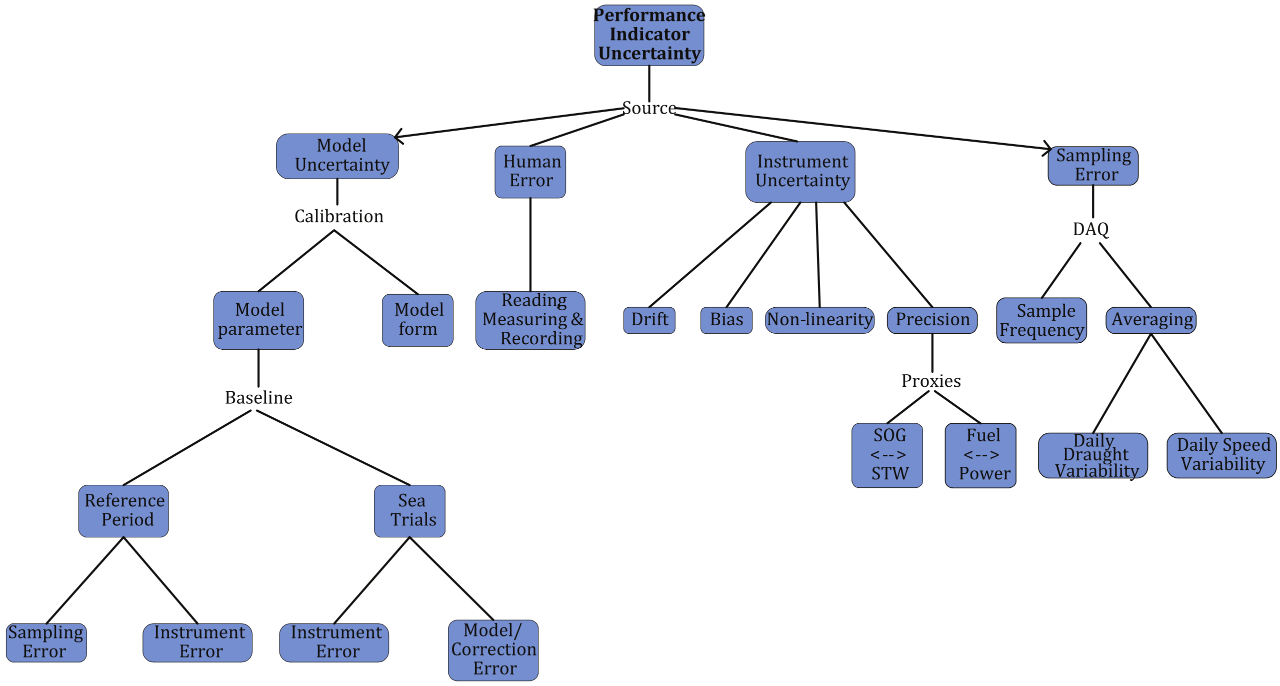


Figure A.2 — Uncertainty sources

The leading components of uncertainty: model uncertainty, sampling error, instrument error and human error, are discussed in greater detail below.

A.4.2 Instrument uncertainty

For each of the sensors included in the analysis (speed/power/draught) the following sensor properties apply:

— Precision: included in the analysis.

— Bias: excluded because, provided the sensor bias is constant, then this will cancel out when % speed loss for consecutive time periods are compared. There is a small, insignificant effect if the vessel is operated in constant power mode owing to the speed reduction between periods; this is assumed to be negligible.

— Drift: will affect the change in % speed loss between periods. The analysis assumes that the sensors are maintained and within calibration limits and so drift is assumed to be negligible. The potential effects of drift are discussed in greater detail in Reference [3].

The effect of crew measuring the BF (wind speed) instead of using an anemometer and weather vane on the uncertainty of the % speed loss through potentially inaccurate filtering of the weather effects is considered negligible and not represented in the results of method c) and d). This is justified because the BF parameter is a filtering parameter rather than a primary variable required for the speed loss performance value extraction.

The estimation of the different levels of precision of the primary parameters and the proxies defined in ISO 19030-3 are derived in greater detail below.

A.4.3 Sampling error

A.4.3.1 Overview

The effects of sampling error are related to the sample size and the impacts of averaging, which in turn is related to sample frequency. Estimates of representative assumptions for each of these effects are obtained by investigating the statistics of operation, environmental condition and performance of a representative ship.

A.4.3.2 Sample size

The proportion of the data that are removed due to filtering (according to the filter criterion defined in ISO 19030-2 and ISO 19030-3) depends on the environmental/operational conditions experienced by the ship. For example, if a ship spends 80 % of its time in weather conditions where wind speed is greater than BF4, then at least 80 % of the measurements of V_d will be omitted from the estimation of the performance value, thereby reducing the sample size used for its calculation. If everything else is equal, a lower sample size will result in a greater performance value uncertainty. The amount of data that is rejected by the filtering process is also a function of the sample frequency. If a low frequency (e.g. daily) sampling is used, then typically a greater proportion of data will be filtered out due to the use of average values in the filter criterion.

Table A.1 — Percent of data remaining after sequential filtering steps (order matters with regards to the relative significance of each filter)

	Number of observations	Cumulative remaining proportion of at-sea data (%)
All data (397 d, 1 sample/15 min)	38 112	
At sea data (and after exclusion of obvious outliers/missing data)	19 717	100
Wind speed < 7,9 m/s	12 881	65,3
Power > 0,3	8 643	43,8
Abs(SOG-STW) < 1 knot	7 344	37,3
Sea depth > criteria	5 636	28,6
Speed within limits	5 625	28,5

Estimates of the effect of filtering on sample size were obtained by inspecting the data measurements of the representative ships. 70 % of the data is assumed to be filtered out as presented in Table A.1. It is recognized that this is ship specific and dependent on the ship's operational profile; the values used are conservative with respect to the uncertainty that may be achieved, and the amount of data filtered out can vary significantly between ships.

A.4.3.3 Sampling frequency and averaging

The daily speed variability [due to accelerations, rudder angle changes, or crew behaviour patterns (slow steaming at night for example)] can introduce errors in the quantification of the performance value when the sampling frequency is low (daily). For these reasons, a level of operating speed variability is introduced into the simulation of the "true" speed at a frequency less than daily. The simulated variability is estimated from the data for the representative ship to be 1,74 % of the daily average speed (after BF >4 is filtered for), this is used as the assumption in the simulation and is included by the addition of normally distributed noise to the underlying ship speed. The effect of averaging daily speed variability is to alter the bias of the overall % speed loss uncertainty (not the precision), this means that if the underlying daily speed variability changes between periods then the % speed loss calculation may be biased. This magnitude of the effect of the bias is included in the calculated results in this annex. The effect of averaging daily draught variability (i.e. due to change in trim or due to the fuel consumed) is not included but assumed to be negligible.

A.4.4 Model uncertainty

When converting measured power into expected speed, the method assumes that the ship speed, power relationship is defined by a cubic. If the true exponent of ship speed is actually between 3,15, as presented by International Marine Coatings[8], and 4,0 for high speed ships such as container vessels[17], then this will cause a change in bias and precision of the % speed loss such that this can result in an increase in the uncertainty of the PV measurement. In the practical application of this method (in ISO 19030-2 and ISO 19030-3), the model uncertainty relates to the possibility that the speed-power reference curve (whether from speed trial, CFD or towing tank test) is not a perfectly accurate representation of the variation in power with ship's speed.

However, since the cause of the resulting bias is likely to be constant in the reference and the evaluation period(s) then their effect on the uncertainty calculation is assumed to be negligible. This assumption is corroborated by further investigation of this source of uncertainty undertaken in Reference [3].

The effect of assuming the Admiralty formula adequately represents changes in draught on ship speed and power has not been investigated, but this is assumed to be negligible relative to other sources of uncertainty.

A.4.5 Human error

Human error (which is often categorised as instrument uncertainty) may occur in any measurements when operating, reading or recording sensor values if the report completion is not automated. For example the noon data entry may not occur at exactly the same time each day, the recording of "time spent steaming" may not be adjusted to compensate for crossing time zones and it is possible that different sensors are used to populate the same field, for example, some crew may report speed from the propeller RPM and others report speed over ground. The measurement of wind speed through crew observations may also be subject to uncertainties. Human error is both difficult to quantify and challenging to generalize since it is dependent on crew and operator procedures which vary from ship to ship as well as company to company. For both of these reasons, it is not included in this analysis, although we realize that the consequence of this exclusion is that the results are likely to underestimate the overall uncertainty.

A.5 Estimates of precision for the different instruments used to obtain primary and secondary parameters

A.5.1 Speed through water

Empirical data is used as the basis to estimate the uncertainty due to the approximation of a ship's speed through the water using a sensor measuring speed over ground. The main source of the uncertainty is the effect of tides and currents on speed through the water which cannot be accounted for when measuring uncertainty. Figure A.3 shows the difference between the measured speed through water and speed over ground of 20 ships (a mixture of tankers and bulk carriers), operating on a number of routes. The data covers a period of 3 years to 5 years per ship, so represents approximately 80 ship years of operation. The average difference is -0,14 knots and the standard deviation is 0,95 knots. For a ship travelling at 19 knots, a standard deviation of 0,95 knots represents a 5 % precision (to 1σ). For ships with lower speed, the precision will be slightly higher and for ships with higher speed, the precision will be slightly lower, but 5 % is considered to be sufficient as a generic representative value for this initial study of uncertainty.

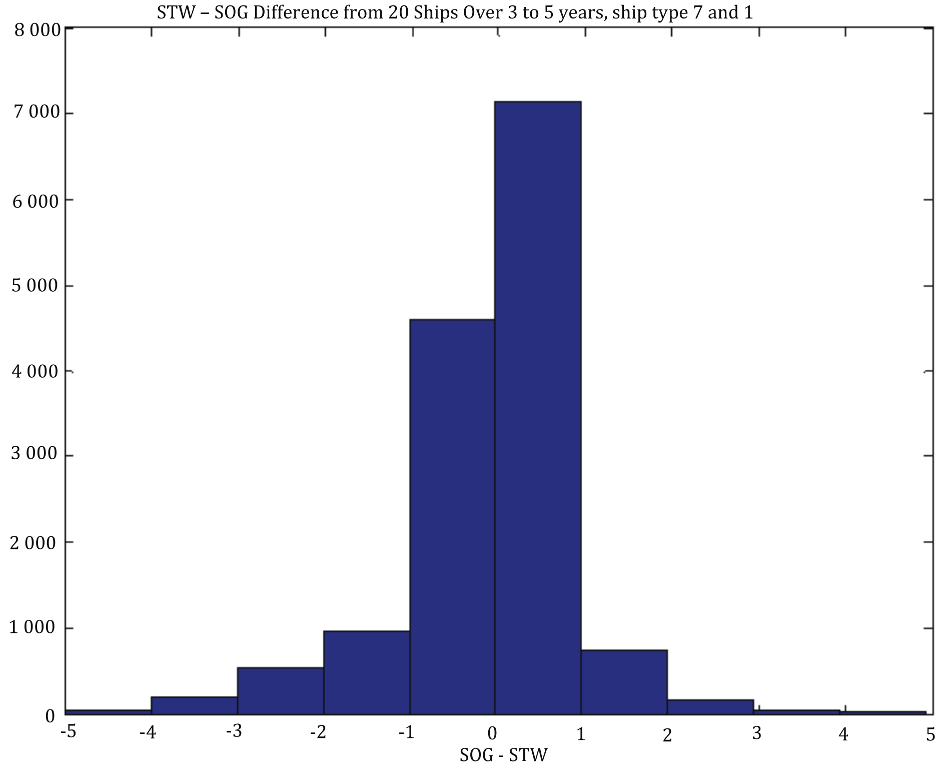
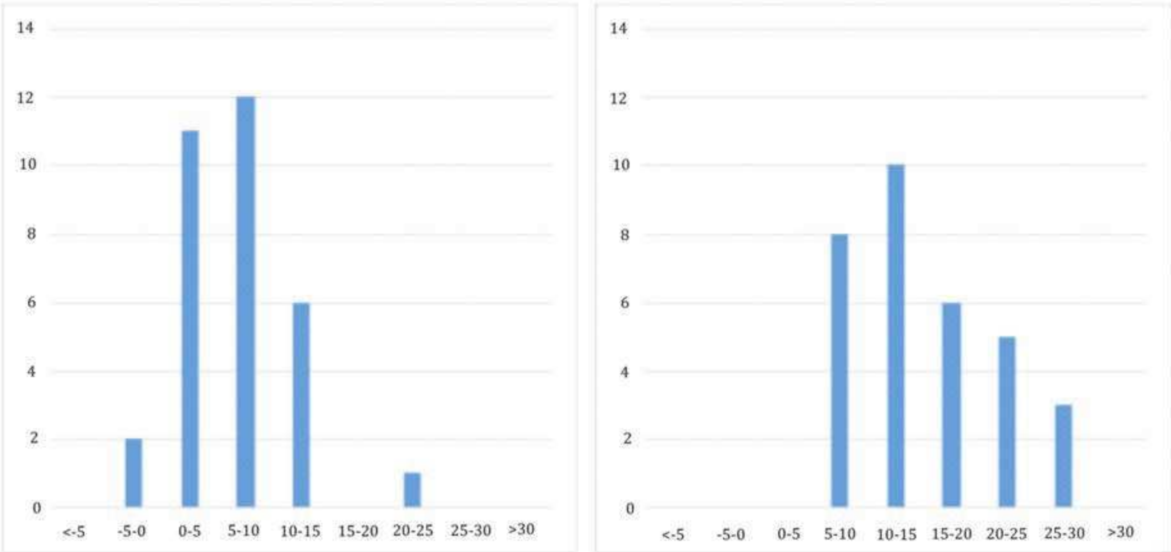


Figure A.3 — Histograms of the difference between speed over ground and speed through water for 20 tankers and bulk carriers

A.5.2 Power

Among other sources of information, data from a sample of nine ships was used to estimate the uncertainty of the measurement of delivered power. All nine ships had shaft torque meter, rpm meter and fuel flow meters, e.g. all nine ships were fitted with sensors that were appropriate for Annex B and Annex C estimation of delivered power in ISO 19030-2:2016. Whilst no third dataset that represented “the truth” was available that these two measurement techniques could be referenced to establish their respective uncertainty in absolute terms, the fact that both measurements in ISO 19030-2:2016, Annex B and Annex C were available for the same ships enabled a comparative uncertainty analysis to be undertaken.

The approach used to quantify uncertainty explored the upper and lower bounds of each method’s uncertainty. One example of the approach used is given in Figure A.3, which shows histograms of the difference between delivered power and indicated power, both for the same ship. Whilst indicated power also contains uncertainty, it is a common reference point against which both ISO 19030-2:2016, Annex B and Annex C methods can be compared. The histograms represent a distribution of data that has an SEM of 4,77% (see ISO 19030-2:2016, Annex B method) and 6,29 % (see ISO 19030-2:2016, Annex C method). These were used to represent approximate upper bounds of each of the methods, and rounded up to incorporate a degree of conservatism (e.g. 5 % and 7 % for Annex B and Annex C respectively).



Difference between ISO 19030-2:2016, Annex B estimated power P_d and indicated power P_i(Pd−P_i)/P_i[%]

Difference between ISO 19030-2:2016, Annex C estimated power P_d and indicated power P_i(Pd−P_i)/P_i[%]

Figure A.4 — Histograms of the difference between delivered power and indicated power for both the ISO 19030-2:2016, Annex B and Annex C method

A.5.3 Draught

No data was available to analyse quantitatively the uncertainty of draught measurement obtained either from draught gauges or from the readings taken at the last port of call. It was agreed by the group that appropriate values for either method's accuracy of 0,1 m (to 1σ).

A.6 Summary of the assumed precisions for four standard approaches

A.6.1 General

Table A.2 shows the sensor accuracies assumed for the uncertainty calculations both for the two variants of the ISO 19030-2, and for each of the four methods defined in ISO 19030-3.

Table A.2 — Percentages denote sensor accuracies (1σ)

Method	Speed	Delivered power	Measurement freq	Draught	Water depth	Rudder angle	Wind speed and direction
ISO 19030-2:2016, Annex B method	Speed log = 3 %	Torque meter and rpm meter = 1,1 % to 5,0 %	Every 15 s[a] with 5 min average = 288/d[b]	Draught gauges = +/-0,1 m	Echo sounder	Rudder angle indicator	Anemometer
ISO 19030-2:2016, Annex C method	Speed log = 3 %	Part 2B Fuel consumption = 5,6 % to 7,0 %					
ISO 19030-3:2016 method 1	Speed log = 3 %	Part 3 Fuel consumption proxy = 10 %	Every 15 s[a] with 5 min average = 288/d[b]	Draught gauges = +/-0,1 m	Echo sounder	Rudder angle indicator	Anemometer
ISO 19030-3:2016 method 2	Proxy using speed over ground = 5 %	Torque meter and rpm meter = 3,6 %	Every 15 s[a] with 5 min average = 288/d[b]	Calculated from draught mark reading from last port of call and tank soundings = +/-0,1 m	Echo sounder	Rudder angle indicator	Anemometer
ISO 19030-3:2016 method 3	Speed log= 3 %	Torque meter and rpm meter = 3,6 %	Daily = 1/d	Calculated from draught mark reading from last port of call and tank soundings = +/-0,1 m	Echo sounder	none	Anemometer
ISO 19030-3:2016 method 4	Proxy using speed over ground = 5 %	Fuel consumption proxy = 10 %	Daily = 1/d	Calculated from draught mark reading from last port of call and tank soundings = +/-0,1 m	Echo sounder	none	Anemometer

[a] Note that in ISO 19030-2, 1/15 s is prescribed as the *minimum* frequency. Uncertainty will not be adversely affected by an increase in logging frequency.

[b] Because all sensor uncertainties are characterized by Gaussian distributions, only random errors are being considered in the simulations, not systematic errors (see Table A.3 for possible sources of systematic errors). This means that as the measurement frequency increases, the effect of sampling dominates the sensor uncertainties and the overall performance value uncertainty tends to be zero. Work on uncertainty in other sectors explains the difference between this theoretical result and empirical measurement of uncertainty as being due to the presence of systematic errors[19]. Methods exist to approximate systematic errors in combination with random errors, e.g. through the use of rectangular probability distributions. Because of a lack of data to define a systematic error's rectangular distribution, in this initial work, an equivalent effect on overall uncertainty is achieved by coarsening the sampling frequency used in the Monte Carlo simulation to once every 15 min (instead of once every 5 min as specified in the method). This ensures that the overall uncertainties are derived with a degree of conservatism; further work is ongoing into alternative approaches.

A.6.2 Simulated ship specification

The specifications of the ship which is used as the basis of the simulation are as follows:

— loaded speed = 14 knots;

— ballast speed = 14 knots;

— loaded draught = 18 m;

— ballast draught = 10 m.

These values are representative of large wet or dry bulk cargo ships. Their application as the basis of a simulation of uncertainties means that if these are not the same as values describing the ship that the estimate of performance value uncertainty is being applied to, the modification to the uncertainties due to the difference in ship specification will be small, and the relative uncertainties of the six method variants and three period durations will remain consistent.

A.6.3 Simulated operational profile

In order to simulate an operational profile, a representative set of parameters are defined (speed and draught), from which the true power is then derived. The specifics of those representative parameters are given and discussed below.

The assumed ship speed, draught and rate of degradation that is defined in the underlying ship profile will not cause changes in the precision of the overall uncertainty however they will bias the result as they are inputs to the method for evaluating the measurand itself. If the operating profile changes markedly between periods, then the uncertainty in the output will be affected through the bias and consequently the root sum square (RSS) of the calculation of total uncertainty.

In some cases, there is evidence of weather seasonality significantly affecting the ship's speed-power relationship (even within the filtered speed range) and therefore this increases the uncertainty with which power from speed is evaluated. This effect does not exist for all ships (one studied case indicated only 0,1 knot difference between average winter and average summer speeds) and is dependent on the cyclical nature of the ship's operating profile, on changes in the ports between which it operates and on the global location of its operations. Since this effect is relatively unpredictable and not easily generalised is excluded from the analysis.

Specific details of the assumed operating profile and associated impact on primary and secondary parameters are detailed below.

Operating profile: The ships loading condition is assumed to be 50 % loaded and 50 % ballast (with associated changes in draught). A baseline vessel speed for a 90 d period (V_{true}) has been assumed where the underlying profile is based on alternating ballast and loaded voyages of 15 d each. The vessel speed voyage variability is represented by a Weibull distribution and some daily speed variability is superimposed.

Environmental effects: The effect of small changes in the weather (within the 0 < BF < 4 filtering criteria) is allowed for by the inclusion of some daily speed variability, assumed to be normally distributed. This also includes other small fluctuations that may not be filtered (acceleration for example).

Time dependent degradation: Assumed to be linear with time and at the rate of 2,6 % per year average speed loss[9]. The degradation is assumed to be independent of ship speed and draught and the ship's power is assumed to increase incrementally at a rate which maintains constant power operation.

A.6.4 Simulated true propulsion power

A representation of the ship's true propulsion power is derived from the speed, draught and technical specification of the ship using the performance model in Formula (A.1). The assumption in the model is of a value of n = 3. The model and the assumed value of n = 3 are common to the performance model incorporated in the bottom-up method in the IMO 3rd GHG Study[9] which was extensively validated in that study against operator's data for a variety of ship types.

$$P_t = \frac{P_{ref}\left(\frac{t_t}{t_{ref}}\right)^{\left(\frac{2}{3}\right)}\left(\frac{V_t}{V_{ref}}\right)^n}{\eta_f} \tag{A.1}$$

where

P_t is the instantaneous power;

V_t is the speed at time, t;

t_t is the draught at time, t;

P_{ref} is the reference power at speed, V_{ref}, and draught, t_{ref};

n is an index that represents the relationship between speed and power;

η_f is the degradation in performance over time (discussed above).

For the purposes of this simulation, the model needs to be representative of how a ship's power demands vary as a function of draught, speed and fouling. However, as this is just a reference against which simulated deviations due to measurement uncertainty are sampled it does not matter if the model is not a precise representation of an actual ship. The speed and draught operational profile described in the previous clause therefore translates into the vessel power output.

A.7 Key assumptions

In order to simplify the range of technical and operational parameters to an extent that makes the modeling simple enough to be computationally tractable, a number of assumptions are made. These assumptions are listed, along with justifications, in Table A.3.

Table A.3 — Summary of assumptions

Assumption	Affect on PI (bias/precision/both?)	Included?	Justification
Sample size	Precision	Yes	
Sensor precisions	Precision	Yes	
Sensor bias	Bias and precision	No	Bias assumed to be constant between time periods and therefore cancels The effect on precision is small and assumed to be negligible
Sensor drift	Both	No	Sensors assumed to be calibrated/ maintained
Speed variability/day	Bias	No	Assumed that between 3-month periods the daily speed variability cancels
Operational profile	Bias	No	Assumed to be similar between 3-month periods
Time dependent effect – P increase	Bias	No	Assumed to be linear with time

Table A.3 *(continued)*

Assumption	Affect on PI (bias/precision/both?)	Included?	Justification
Time dependent effect – V loss	Precision	No	Insignificant (e.g. V loss changed from ~40 % to 5 % over 90 d -> uncertainty is reduced by 0,29 %)
Model error	Bias – if the operating conditions are the same in the reference and evaluation period, model error induces negligible bias. If they are not the same, significant bias can be induced. Precision – model error can also have a moderate impact on the precision	No	Whilst these can be significant, the assumption made is that the sourcing of the speed, draft, trim and power relationship is done rigorously such that the data used is a good likeness to the ship's actual performance.
Human error	Both	No	Cannot be quantified

Overall, there are two main justifications for the acceptability of these assumptions.

a) The evidence supplied by the comparison between the performance uncertainty estimate calculated using a Monte Carlo simulation and the performance uncertainty estimate obtained by inspecting measured data, as presented in Reference [3].

b) The fact that these assumptions are predominantly common to both the reference and evaluation periods and therefore should be removed by the use of the performance indicators, which look at relative rather than absolute performance.

A.8 Outputs from the simulation and estimation of performance value uncertainty

A.8.1 General

Each time step (daily or 1/15 s) a pdf represents the uncertainty of the % speed loss performance indicator which is the combined effect of each source of uncertainty propagated through the model by the Monte Carlo method. Figure A.5 presents the calculated per cent speed loss for each daily averaged sample; the error bars indicate the standard deviation.

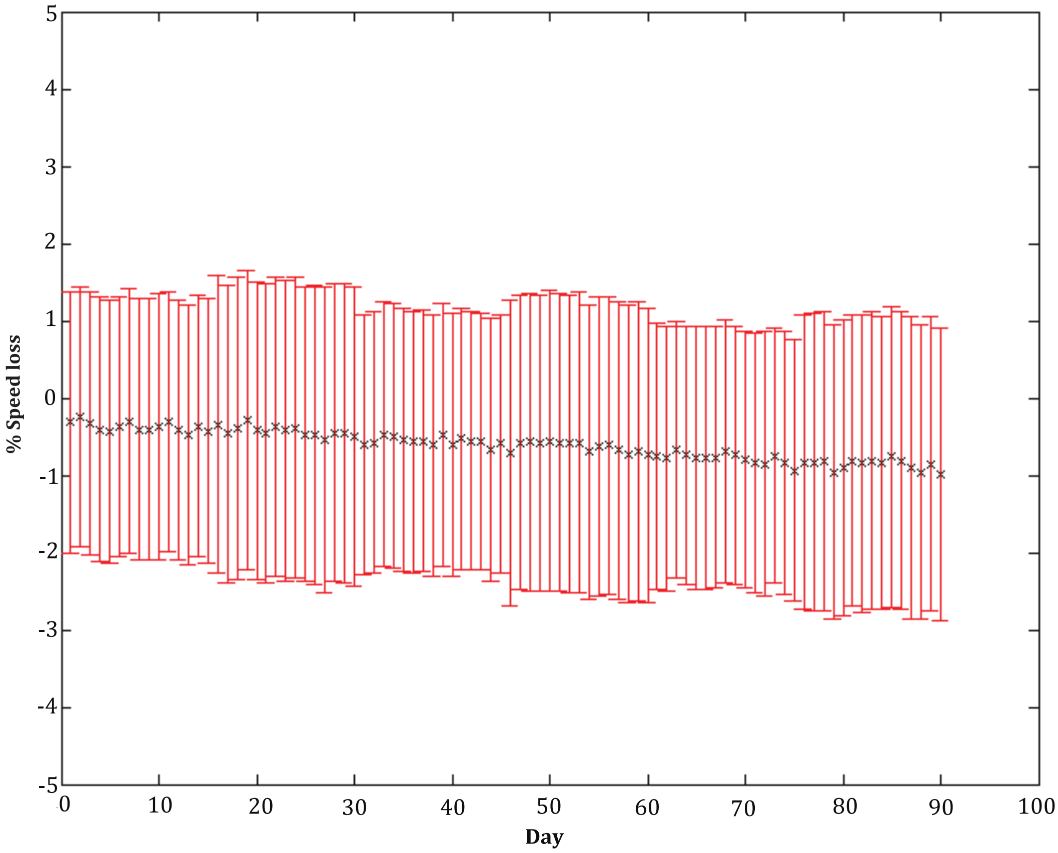


Figure A.5 — MC output of mean and standard deviation error bars of mean percent speed loss

Each evaluation period (3, 6 or 12 mo), the standard error of the mean (SEM) is calculated by randomly sampling from the pdf at each time step.

$$\mathrm{SEM} = S\left(\overline{V_\mathrm{d}}\right) = \frac{2\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(V_{\mathrm{d}_j} - \overline{V_\mathrm{d}}\right)^2}}{\sqrt{n}} \tag{A.2}$$

This is done repeatedly and the average SEM calculated.

The SEM quantifies how precisely the true mean of the population is known. It takes into account both the value of the SD and the sample size, i.e. given the scatter in the speed loss calculation for each time step (owing to measurement uncertainties etc.), the SEM indicates how close the actual average speed loss is to the sampled average speed loss. The 95 % confidence interval is given by +/-2 × SEM.

The effect of any of the sources of uncertainty may be to alter the precision in the daily % change in speed loss, or to cause a bias in the result. A factor that causes the bias to change however will cancel out so long as the cause of the bias is constant in the reference and the evaluation period. Therefore, the results in A.8.1 are presented in the form of the standard error of the mean given the precision (standard deviation) of the daily uncertainty probability distributions.

A.8.2 Estimations of performance value uncertainty

Table A.4 presents the uncertainty, $u_{\overline{V_\mathrm{d}}}(\%)$ a 95 % confidence interval, as calculated using the method described above. The values in Table A.4 are absolute uncertainties for the specified simulation which all assume a rate of speed loss of 2,4 % reduction per annum. Sensitivity tests were performed for changes to the assumed rate of speed loss and no significant impact on absolute uncertainty was observed, consequently these values can be assumed to be broadly applicable to a range of performance values and rates of change of performance over time.

The values of uncertainty for both the ISO 19030-2:2016 methods (described in Annexes B and C) are estimated for their respective range of values for the accuracy of P_d listed in Table A.2. For the methods described in ISO 19030-3, only a single value of the P_d uncertainty is used. The simulation parameters and assumptions are considered to be representative for the ship types and sizes for which this document is intended. However, the technical and operational specifics of an individual ship could create significant differences in the uncertainties of the different part's measurement methods. Consequently, it is advised that when using these quantifications of uncertainty, careful attention is paid to ensure the applicability of the key assumptions (A.7) and these results are treated as indicative values only.

Table A.4 — Indicative uncertainty (%) to 95 % confidence interval

	3-month period	6-month period	12-month period
ISO 19030-2:2016, Annex B method	0,33 % – 0,38 %	0,24 % – 0,27 %	0,17 % – 0,19 %
ISO 19030-2:2016, Annex C method	0,39 % – 0,42 %	0,28 % – 0,30 %	0,20 % – 0,21 %
ISO 19030-3-1	0,50 %	0,36 %	0,25 %
ISO 19030-3-2	0,57 %	0,40 %	0,29 %
ISO 19030-3-3	3,40 %	2,46 %	1,76 %
ISO 19030-3-4	6,30 %	4,57 %	3,25 %

The results in Table A.4 reveal that there can be large differences between the uncertainty of performance measurements obtained using the ISO 19030-2 methods in this document and some of the ISO 19030-3 methods (particularly, methods 3-3 and 3-4 which make use of noon report data). The table also reveals that there is comparatively little difference in uncertainty both

— across the range of P_d uncertainty values associated with each of the ISO 19030-2 methods, and

— between the method described in ISO 19030-2:2016, Annex B and Annex C.

The explanation for this is that, due to the details of the performance value calculation and the estimated value for speed sensor uncertainties, the speed through water measurement uncertainty has a dominating influence on the overall performance value uncertainty.

To provide clear and simple guidance to the user, a single value of uncertainty for both ISO 19030-2:2016, Annexes B and C is defined and listed in Table A.5. This value is calculated by taking the average between the maximum and minimum values across the full range of values listed for both ISO 19030-2:2016, Annexes B and C uncertainties.

This is a pragmatic solution to the challenge of describing a single representative value for each of the methods in ISO 19030-2:2016, Annexes B and C. The lowest levels of uncertainty are all achieved using ISO 19030-2:2016, Annex B. Furthermore, as the speed sensor's uncertainty improves the difference in uncertainty between the methods in ISO 19030-2:2016, Annexes B and C increases. If the measurement application requires the lowest possible levels of uncertainty, and particularly if the speed measurement uncertainty is known to be lower than the values specified in Table A.2, the ISO 19030-2:2016, Annex B method should be preferred over the ISO 19030-2:2016, Annex C method.

Table A.5 — Finalized indicative performance value uncertainty (%)

	3-month period	**6-month period**	**12-month period**
ISO 19030-2 methods	0,38 %	0,27 %	0,19 %
ISO 19030-3-1	0,50 %	0,36 %	0,25 %
ISO 19030-3-2	0,57 %	0,40 %	0,29 %
ISO 19030-3-3	3,40 %	2,46 %	1,76 %
ISO 19030-3-4	6,30 %	4,57 %	3,25 %

One of the most significant input to the uncertainty in the performance value is the speed sensor precision. This is examined in a one-at-a-time sensitivity analysis presented in Reference [3] and a comparison is made of the effects using a sensitivity index. Altering only the speed sensor precision from 5 % to 1 % changes the performance value uncertainty from 2,5 % to 0,6 % (for a specific ISO 19030-2 method equivalent sensor configuration example).

A.8.3 Estimations of performance indicator uncertainty

The uncertainty of the PI quantification must be calculated from the estimates of the uncertainty in the period average performance values from which the PI is calculated. The procedure for calculation of PI uncertainty is given in Formula (A.3), with the inputs to the formula provided by the performance value uncertainties given in Table A.5. This quantification of uncertainty must be included in any documentation containing values of the performance indicator. If the reference and evaluation period have the same duration, then the average performance value uncertainties, which form the input to the calculation, will be the same. In such cases, the performance indicator uncertainty is the product of √2 and the performance value uncertainty, as listed in Table A.4. In the situation where the reference and evaluation periods do not have the same duration, the value of performance indicator uncertainty must be calculated using Formula (A.3):

$$u_{k_{\mathrm{HP}}} = \sqrt{u_{v_{\mathrm{d,eval}}}{}^2 + u_{v_{\mathrm{d,ref}}}{}^2} \qquad \text{(A.3)}$$

where

$U_{k_{\mathrm{HP}}}$ is the uncertainty (to 95 % confidence interval) of the estimated PI value;

$U_{v_{\mathrm{d,eval}}}$ is the uncertainty (to 95 % confidence interval) of the calculated percentage speed loss during the evaluation period;

$U_{v_{\mathrm{d,ref}}}$ is the uncertainty (to 95 % confidence interval) of the calculated percentage speed loss during the reference period.

Table A.6 — Estimates of the performance indicator uncertainty, to a 2 sigma, 95 % confidence interval for specific combinations of measurement parameters and reference and evaluation period[a]

	3 (90 d)	6 (180 d)	12 (360 d)
ISO 19030-2 methods	0,53 %	0,38 %	0,27 %
ISO 19030-3-1	0,71 %	0,50 %	0,35 %
ISO 19030-3-2	0,80 %	0,57 %	0,40 %
ISO 19030-3-3	4,80 %	3,47 %	2,49 %
ISO 19030-3-4	8,89 %	6,44 %	4,58 %

a Accuracy will not be adversely affected by an increase in logging frequency.

In general terms, the absolute uncertainty is reduced through any of the following:

— increasing the accuracy of sensors and measurements of the PI calculation's inputs;

— increasing the frequency of measurements;

— increasing the time period of the reference and evaluation period.

The results in Tables A.5 and A.6 give an indication of the sensitivity of the uncertainty to variations in these specifications. If using a non-standard combination of sensors and measurements, this can guide the user towards an expected uncertainty. However, the interaction of the different sources of uncertainty is not straightforward and so for anything other than small variations to the three standard procedures defined in Table A.5, it may be necessary to reapply the method described in this annex in order to estimate the impact on performance value uncertainty.

The uncertainty of the PI (i.e. the magnitude of the uncertainty to the magnitude of the PI), is influenced by the specifications of the measurement parameters and measurement procedure, as well as by the magnitude of the PI. When this document is applied to measure small changes in performance, a lower uncertainty is likely to be required than when measuring large changes in performance.

This document does not dictate a minimum level of uncertainty in the PI. Different levels of uncertainty may be appropriate to different applications, depending on the criticality or risk associated with the decision.

A.8.4 Worked example of performance indicator uncertainty

A worked example is presented to demonstrate how the uncertainty of the performance value and the performance indicator are obtained.

Assuming a ship that

— at time $t = 0$ has a performance value equal to 0,

— has a performance indicator of -2,4, e.g. that shows a decrease in speed of 2,4 % per annum (due to changes in hull and propeller performance), and

— the reference and evaluation period are a year each, as in the dry-docking or in-service performance indicators.

Then PV in the reference period will be -1,2 and PV in the evaluation period will be -3,6. Table A.7 shows for each method variant the PV uncertainty and upper and lower bounds (consistent with a 95 % confidence interval). Table A.7 also shows that the consequent PI uncertainty is 0,27 % for the method in ISO 19030-2 and 4,6 % for the method 4 in ISO 19030-3. In ISO 19030-3, the uncertainty can be up to 200 % of the measurand.

Table A.7 — Estimates of the uncertainty, to a 2 sigma, 95 % confidence interval for the case of a ship with a performance indicator of -2,4 % and a reference and evaluation period of 12 months

Method	ISO 19030-2	ISO 19030-3-1	ISO 19030-3-2	ISO 19030-3-3	ISO 19030-3-4
PV ref uncertainty +/-	0,19 %	0,25 %	0,29 %	1,76 %	3,25 %
PV eval uncertainty +/-	0,19 %	0,25 %	0,29 %	1,76 %	3,25 %
PV ref upper bound	-1,39 %	-1,45 %	-1,49 %	-2,96 %	-4,45 %
PV ref lower bound	-1,01 %	-0,95 %	-0,91 %	0,56 %	2,05 %
PV eval upper bound	-3,79 %	-3,85 %	-3,89 %	-5,36 %	-6,85 %
PV eval lower bound	-3,41 %	-3,35 %	-3,31 %	-1,84 %	-0,35 %
PI uncertainty +/-	0,27 %	0,35 %	0,41 %	2,49 %	4,60 %

Extending this example, for the same ship, if the reference and evaluation period are 3 mo each, as in the maintenance trigger or maintenance effect performance indicators, then PV in the reference period will be -0,3 and PV in the evaluation period will be -0,9. The corresponding PI being -0,6. Table A.8 then shows the overall PI uncertainty of 0,54 % for the method in ISO 19030-2 and 8,91 % for the method 4 in ISO 19030-3.

Table A.8 — Estimates of the uncertainty, to a 2 sigma, 95 % confidence interval for the case of a ship with a Performance Indicator of -2,4 and a reference and evaluation period of 3 mo

Method	ISO 19030-2	ISO 19030-3-1	ISO 19030-3-2	ISO 19030-3-3	ISO 19030-3-4
PV ref uncertainty +/-	0,38 %	0,50 %	0,57 %	3,40 %	6,30 %
PV eval uncertainty +/-	0,38 %	0,50 %	0,57 %	3,40 %	6,30 %
PV ref upper bound	-0,68 %	-0,80 %	-0,87 %	-3,70 %	-6,60 %
PV ref lower bound	0,08 %	0,20 %	0,27 %	3,10 %	6,00 %
PV eval upper bound	-1,88 %	-2,00 %	-2,07 %	-4,90 %	-7,80 %
PV eval lower bound	-1,12 %	-1,00 %	-0,93%	1,90 %	4,80 %
PI uncertainty +/-	0,54 %	0,71 %	0,81 %	4,81 %	8,91 %

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