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Level 1 vulnerability criterion for the dead ship condition: A practical methodology for embedding operational limitations

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ABSTRACT

The framework of second generation intact stability criteria (MSC.1/Circ.1627) allows introducing so-called "operational limitations", by specifying alternative environmental conditions based on the expected operation of the ship. Relevant calculation parameters of the criteria are correspondingly modified, according to standardized procedures specified by the Explanatory Notes. This is a significant novelty, and information is available for implementing operational limitations for most of the failure modes and levels of assessment. However, this is not the case for the level 1 vulnerability criterion for the dead ship condition. Therefore, the paper investigates the development of a rational simple procedure to contribute filling this gap. The devised approach provides a tool for determining a modified reference wind speed based on the environmental conditions representative of the considered operational limitations. Specifically, the modified wind speed is defined as the wind speed with a specified probability of exceedance. The reference probability of exceedance is determined considering the standard conditions and assumptions in the framework of MSC.1/Circ.1627. The modified reference wind speed can then be used to re-define all the calculation parameters of the criterion, according to the relevant theoretical background. Two example applications of the devised approach are also provided.

1. Introduction

After many years of development, the Maritime Safety Committee of the International Maritime Organization (IMO) has approved the Interim Guidelines on the second generation intact stability criteria as MSC.1/Circ.1627 (IMO, 2020). The corresponding Explanatory Notes have been recently approved and are under editorial finalization (IMO, 2022a).

The main target of MSC.1/Circ.1627 (IMO, 2020) is to provide approaches for intact stability assessment with respect to some potentially dangerous dynamic stability phenomena that, presently, are not properly covered by the 2008 IS Code (IMO, 2022b). Considering the novelty of the approaches in the framework of second generation intact stability criteria, MSC.1/Circ.1627 (IMO, 2020) has an interim non-mandatory nature for trial use, and one of the targets of the interim guidelines is to gain experience in the application of the developed criteria. The experience gained in the trial application period is expected to also support future revisions of the guidelines and/or the associated explanatory notes, if deemed necessary.

One important novelty of the framework of second generation intact stability criteria is the possibility of implementing so-called "operational measures" (see chapter 4 in MSC.1/Circ.1627 (IMO, 2020)). In this respect, §5 of the Preamble of MSC.1/Circ.1627 (IMO, 2020) recognizes that, in general, "an integrated perspective, combining design methods and operational measures, is the most effective way for properly addressing and continuously improving safety against accidents related to stability for ships in a seaway". Furthermore, with relevance to those cases where the user identifies a need to account for specific operational characteristics of the ship, §4.1.1 of MSC.1/Circ.1627 (IMO, 2020) adds that "a combined consideration of design and operational aspects can effectively be used to achieve a sufficient safety level". Therefore, it can be recognized that the framework of MSC.1/Circ.1627 (IMO, 2020) embeds an underlying intention to provide standardized approaches to guarantee a uniform safety level through a virtuous combination of design methods and proper consideration of ship-specific operational characteristics, when this is relevant.

Operational measures comprise, in general, "operational limitations" and "operational guidance" (see chapter 4 in MSC.1/Circ.1627 (IMO, 2020)). Operational limitations, in particular, allow designing a vessel with reference to a specific operational area or route and, if appropriate,

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season. Operational limitations also allow the possibility of embedding limitations related to the maximum significant wave height. From an application perspective, area/route-specific environmental conditions and/or limitations on the maximum significant wave height can be embedded in some of the criteria, either directly, or through a corresponding modification of the calculation parameters. Standardized procedures for modifying the calculation parameters are specified by the Explanatory Notes (IMO, 2022a).

The possibility of introducing operational measures in the framework of second generation intact stability criteria is gaining increasing attention (e.g. Umeda et al., 2007; Bačkalov et al., 2016; Hashimoto et al., 2017; Rudaković and Bačkalov, 2019; Rinauro et al., 2020; Hashimoto and Furusho, 2021; Paroka et al., 2021; Petacco and Gualeni, 2021; Shigunov et al., 2021; Bulian and Orlandi, 2022), because it represents a significant evolution of paradigm compared to the existing intact stability assessment framework of the 2008 IS Code (IMO, 2022b).

The Explanatory Notes (IMO, 2022a) provide the background information for a standardized uniform implementation of operational limitations for most of the failure modes and levels of assessment, but not for all of them. A notable exception is the level 1 vulnerability criterion for the dead ship condition (shortly, DS-L1 criterion hereinafter). For the DS-L1 criterion the possibility of embedding operational limitations is available in principle from MSC.1/Circ.1627 (IMO, 2020), but without specific implementation guidance. In contrast, the level 2 vulnerability criterion for the dead ship condition (shortly, DS-L2 criterion hereinafter) allows a straightforward implementation of operational limitations.

Hence, an element is missing in the framework of MSC.1/Circ.1627 (IMO, 2020), and this requires proper consideration.

It is further noted that, according to MSC.1/Circ.1627 (IMO, 2020), only part of the full set of operational measures is applicable in case of the dead ship stability failure mode. This is a consequence of the fact that, in dead ship condition, the main propulsion plant and auxiliaries are considered inoperable. Therefore, the master cannot control course and speed of the ship, and the ship cannot actively avoid heavy weather conditions. This eventually reduces the spectrum of operational measures that are considered relevant for the dead ship condition failure mode. Specifically, only operational limitations related to areas or routes and season can be applied. Instead, operational limitations related to maximum significant wave height and operational guidance cannot be applied. This is actually clarified by §4.1.3 in MSC.1/Circ.1627 (IMO, 2020).

Therefore, in this work, the term “operational limitations” related to the dead ship condition failure mode is always implicitly intended in the limits specified by MSC.1/Circ.1627 (IMO, 2020). Accordingly, the implementation of operational limitations for the dead ship condition is herein meant to reflect the operation of the ship in a specified area or route and season, according to §2.2.1.3.2, §4.1.3, §4.3.1.1.1 and §4.5.1 in MSC.1/Circ.1627 (IMO, 2020).

As clarified in the Explanatory Notes (IMO, 2022a), the DS-L1 criterion directly derives from the Weather Criterion in the 2008 IS Code (IMO, 2022b), with the substitution of the original wave steepness table with the extended wave steepness table from MSC.1/Circ.1200 (IMO, 2006). Accordingly, the DS-L1 criterion can be considered to inherit the whole theoretical/semi-empirical background of the original Weather Criterion.

The background of the Weather Criterion is described in MSC.1/Circ.1281 (IMO, 2008b). In addition, SLF 51/4/1-Annex 1 (IMO, 2008a) provides a detailed description of the modification of the calculation parameters of the Weather Criterion for Japanese ships engaged in restricted services (see also Yamagata, 1959). In particular, three categories of ships are considered (Coasting-II, Coasting-I and Ocean-going), depending on the navigation area. For each category, a corresponding mean wind speed is provided, on the basis of which the wind pressure and the wave steepness table of the Weather Criterion are recalculated. It is worth noting that the same calculation parameters as for Coasting-II ships from SLF 51/4/1-Annex 1 (IMO, 2008a) have also been embedded in the framework of the Weather Criterion by the Maritime & Coastguard Agency, for vessels in UK categorized waters (MCA, 2020).

Therefore, considering that the DS-L1 criterion derives directly from the Weather Criterion, it seems reasonable to try capitalizing on the reported regulatory experience. However, the referred approaches provide rigid ship categories, and they do not allow modifications of the calculation parameters based on generic environmental conditions. Instead, such a flexibility is necessary in the framework of MSC.1/Circ.1627 (IMO, 2020). Therefore, some further steps are necessary for devising a generalized approach for application in the framework of second generation intact stability criteria.

To contribute filling the identified gap, the paper investigates the development of a rational simple procedure for embedding operational limitations in the DS-L1 criterion, taking into account the above-mentioned, already existing, regulatory background, as well as the well-known background of the Weather Criterion.

Specifically, the scope is to provide a means for adjusting the main calculation parameters of the criterion, i.e. wind pressure and wave steepness table, on the basis of environmental data associated with specified operational limitations. Attention is paid to the internal consistency of the regulatory framework, by making reference to the standard environmental conditions and to the reference standard assumptions of the DS-L2 criterion in MSC.1/Circ.1627 (IMO, 2020). Results of this study have been preliminarily presented by Bulian and Francescutto (2021).

The paper is organised as follows. First, in section 2, the background of the DS-L1 criterion is summarised, making reference to the relevant background of the Weather Criterion. Then, section 3 describes the devised procedure for embedding operational limitations in the DS-L1 criterion. Subsequently, section 4 provides some example applications of the devised procedures. Finally, some concluding remarks are reported.

2. Background of the level 1 vulnerability criterion for the dead ship condition

As already recalled, the background of the Weather Criterion has been described in MSC.1/Circ.1281 (IMO, 2008b), SLF 51/4/1-Annex 1 (IMO, 2008a) and, in the vast majority of its aspects, by Yamagata, 1959. This section provides a summary aimed at clarifying the use of this background for the introduction of operational limitations in the DS-L1 criterion.

2.1. Summary of the criterion

As reported by the Explanatory Notes (IMO, 2022a), the present DS-L1 criterion in MSC.1/Circ.1627 (IMO, 2020) corresponds to the well-known Weather Criterion in the 2008 IS Code (IMO, 2022b), but with the extended wave steepness table from MSC.1/Circ.1200 (IMO, 2006). The wave steepness table of the DS-L1 criterion extends the range of directly covered roll periods from 6s ÷ 20s in the Weather Criterion, to 6s ÷ 30s in the DS-L1 criterion. This extension can also be linked to some concerns raised in the past regarding the perceived excessive severity of the Weather Criterion for ships with large natural periods (Francescutto et al., 2001; Francescutto and Serra, 2001; IMO, 2002).

With the exception of the modification of the wave steepness, the rest of the DS-L1 criterion is fundamentally unchanged compared to the Weather Criterion. For the sake of ease of reference, the scheme of the criterion is reported in Fig. 1, and the relevant requirements can be summarised as follows:

$$\begin{cases} \varphi_0 \leq \min(16\,\text{deg}, 0.8\varphi_d) \\ \text{Area } b \geq \text{Area } a \end{cases} \tag{1}$$

where φ_0 is the angle of heel under action of steady wind and φ_d is the

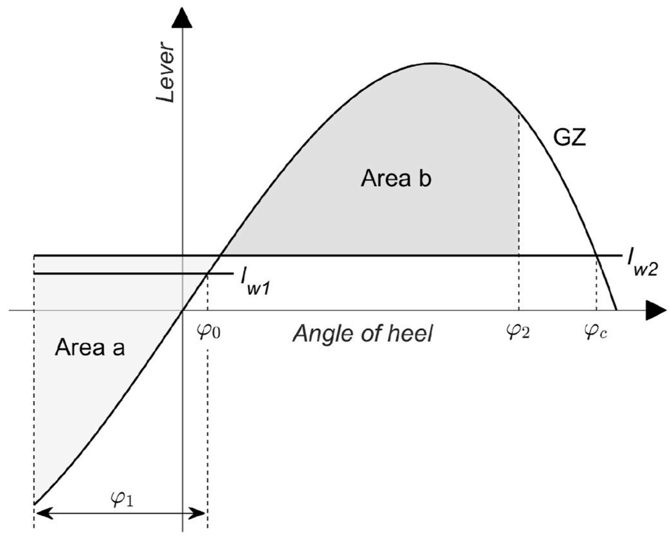

Fig. 1. Scheme of DS-L1 criterion.

angle of deck edge immersion. Details of the DS-L1 criterion can be found in MSC.1/Circ.1627 (IMO, 2020).

As it is evident and well known, there are two main parameters affecting the severity of the criterion, namely, the steady wind heeling lever l_{w1} (from which the gust heeling lever is obtained as $l_{w2} = 1.5 \cdot l_{w1}$), and the angle of roll to windward due to wave action, φ_1.

The wind heeling lever l_{w1} can be determined as:

$$l_{w1} = \frac{P \cdot A_L \cdot Z}{\rho_w \cdot g \cdot \nabla} \tag{2}$$

where P [Pa] is the wind pressure, A_L [m^2] is the projected lateral area of the portion of the ship and deck cargo above the waterline, Z [m] is vertical distance from the centre of A_L to the centre of the underwater lateral area or approximately to a point at one-half the mean draft, ρ_w [kg/m^3] is the water density, g [m/s^2] is the gravitational acceleration, ∇ [m^3] is the underwater hull volume.

In the standard DS-L1 criterion, exactly as in the Weather Criterion, the wind pressure is taken as $P = 504 \ Pa$. However, the DS-L1 criterion also indicates that the value of P "may be reduced" in case operational limitations are introduced (IMO, 2020).

The angle of roll to windward due to wave action, φ_1 [deg], is calculated as follows:

$$\varphi_1 = 109 \cdot k \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s} \tag{3}$$

where the factors k, X_1, X_2 are factors related to damping, r is the effective wave slope coefficient and s is the wave steepness. Calculation details for these factors are provided by MSC.1/Circ.1627 (IMO, 2020).

The wave steepness s shall be determined for a beam regular wave having period equal to the ship natural roll period, in accordance with the standard wave steepness table. The standard wave steepness table is reported, for ease of reference, in Table 1. However, the DS-L1 criterion also indicates that, for ships subject to operational limitations, the wave steepness "may be modified" (IMO, 2020).

As described, according to MSC.1/Circ.1627 (IMO, 2020), both the wind pressure P and the wave steepness s in the DS-L1 criterion may be modified if operational limitations are introduced. However, there are no specific indications on how this should actually be done, neither in MSC.1/Circ.1627 (IMO, 2020) nor in the corresponding Explanatory Notes (IMO, 2022a).

2.2. Background for pressure P

The background for the wind pressure P is described in detail in MSC.1/Circ.1281 (IMO, 2008b).

The heeling moment due to wind and corresponding hydrodynamic reaction, shortly, the wind heeling moment, is expressed as follows:

$$M_w = \frac{1}{2} \cdot \rho_{air} \cdot V_w^2 \cdot C_M \cdot A_L \cdot Z = P \cdot A_L \cdot Z \tag{4}$$

where ρ_{air} [kg/m^3] is the air density, V_w [m/s] is the wind speed, C_M [-] is a heeling moment coefficient, and A_L [m^2] and Z [m] have been previously defined. According to (4), it follows that:

$$P = \frac{1}{2} \cdot \rho_{air} \cdot V_w^2 \cdot C_M \tag{5}$$

In the Weather Criterion, and, as a consequence, in the DS-L1 criterion, the moment coefficient is taken as $C_M = 1.22$ and the reference wind speed is taken as $V_w = 26 m/s$. Considering an air density $\rho_{air} = 1.222 kg/m^3$, the pressure $P = 504 \ Pa$ is obtained. It is important to underline that the definition of the standard pressure P embeds the assumed wind moment coefficient C_M.

It is clear from the reported background that, in case of introduction of operational limitations, the wind pressure P can be modified for a new reference wind speed V_w by directly using the expression (5). In case the moment coefficient C_M is kept to the same value assumed by the standard DS-L1 criterion, the wind pressure P [Pa] can be equivalently modified by using the following simpler expression:

$$P = 504 \cdot \left(\frac{V_w}{26} \right)^2 \tag{6}$$

Operational limitations can therefore be embedded in the calculation wind pressure P by specifying a properly modified wind speed V_w.

It is important to note that the DS-L1 criterion also allows using alternative approaches for the determination of the wind heeling lever l_{w1}. In this respect, reference is made to the procedures in MSC.1/Circ.1200 (IMO, 2006). As a basis, for standard conditions, the corresponding standard wind speed is taken as $V_w = 26 m/s$. However, also when alternative approaches are used for the determination of l_{w1}, MSC.1/Circ.1627 (IMO, 2020) indicates that the value of wind velocity "may be reduced" for ships subjects to operational limitations. Therefore, also in this context, the specification of a modified reference wind speed V_w is sufficient to embed the effect of operational limitations.

2.3. Background for wave steepness factor s

Similarly to the pressure P, also the background for the wave steepness table of the Weather Criterion is described in detail in MSC.1/Circ.1281 (IMO, 2008b). Additional details are also given by Yamagata, 1959 and SLF 51/4/1-Annex 1 (IMO, 2008a). Information related to the extended wave steepness table embedded in the DS-L1 criterion can be found in SLF 45/6/5 (IMO, 2002).

Table 1
Standard wave steepness table in the level 1 vulnerability criterion for the dead ship condition.

Natural roll period, T_r [s]	Wave steepness factor, s [-]
≤6	0.100
7	0.098
8	0.093
12	0.065
14	0.053
16	0.044
18	0.038
20	0.032
22	0.028
24	0.025
26	0.023
28	0.021
≥30	0.020

The wave steepness table in the DS-L1 criterion originates from an assumed relation between wave period, T_{wave}, and wave steepness, s, with the additional assumption that the wave period is equal to the ship natural roll period, T_r . This latter equivalence reflects the linear roll resonance condition.

The relation $s(T_{wave})$ is derived from an adaptation of the relation between the so-called wave age β and the wave steepness s, as originally provided by Sverdrup and Munk (1947).

The wave age, β, is defined as the ratio between the wave celerity, c_{wave}, and the wind speed, V_w. Using the linear dispersion relation in deep water, the wave age can be expressed as:

$$\beta = \frac{c_{wave}}{V_w} = \frac{g \cdot T_{wave}}{2 \cdot \pi \cdot V_w} \quad (7)$$

The simplification embedded in the Weather Criterion keeps a conservatively high steepness in the region of small β, and a constant, conservative, wave steepness in the region of high β. Details in this respect are provided in MSC.1/Circ.1281 (IMO, 2008b), in SLF 51/4/1-Annex 1 (IMO, 2008a) and by Yamagata, 1959.

The same simplification is also embedded in the DS-L1 criterion, although in this case the table of the wave steepness, as already said, has been extended in the region of large roll periods (corresponding to large values of β) by using the wave steepness table in MSC.1/Circ.1200 (IMO, 2006).

The DS-L1 criterion, following the Weather Criterion, assumes an underlying standard reference wind speed of 26 m/s. Fixing the wind speed, and using the linear roll resonance condition $T_{wave} = T_r$, it is possible to derive a relation between natural roll period T_r and wave steepness s, starting from a wind-speed-independent relation between the wave steepness s and the wave age β. This derivation is fully described in MSC.1/Circ.1281 (IMO, 2008b), in SLF 51/4/1-Annex 1 (IMO, 2008a), and by Yamagata, 1959.

In the context of this work, however, it is useful to go back to a relation between wave age at natural roll period, β_r, and wave steepness, s, in such a way that this relation can be used also in case of a modified reference wind speed based on the implementation of operational limitations.

To this end, the standard table of wave steepness reported in Table 1 is transformed to an equivalent dimensionless wave steepness table using the standard reference wind speed $V_w = 26m/s$. The result is reported in Table 2.

Reporting the wave steepness table in the dimensionless form of Table 2 is beneficial from a practical application perspective in the framework of introduction of operational limitations. In fact, as a basis, Table 2 is fully equivalent to the standard wave steepness table in the DS-L1 criterion (Table 1). In addition, it has a more general use in the context of implementation of operational limitations, because it directly and straightforwardly allows embedding a modified reference wind speed V_w.

Table 2
Standard wave steepness table in the level 1 vulnerability criterion for the dead ship condition, in the form of wave steepness as function of wave age at natural roll period.

Wave age at natural roll period, $\beta_r = \frac{g \cdot T_r}{2 \cdot \pi \cdot V_w}$ [-]	Wave steepness, s [-]
≤0.360	0.100
0.420	0.098
0.480	0.093
0.721	0.065
0.841	0.053
0.961	0.044
1.081	0.038
1.201	0.032
1.321	0.028
1.441	0.025
1.561	0.023
1.681	0.021
≥1.802	0.020

It is also important to note that the use of the dimensionless Table 2 for the determination of the wave steepness factor s, is essentially equivalent, from a conceptual perspective, to the procedure described in SLF 51/4/1-Annex 1 (IMO, 2008a). However, SLF 51/4/1-Annex 1 (IMO, 2008a) refers to the wave steepness table in the Weather Criterion, whereas Table 2 embeds the extension to large values of β_r in line with the DS-L1 criterion. For the sake of completeness, it is noted that some small numerical differences between the use of Table 2 and the data in SLF 51/4/1-Annex 1 (IMO, 2008a) in the region of β_r relevant to the Weather Criterion are related to the data smoothing used in SLF 51/4/1-Annex 1 (IMO, 2008a).

Furthermore, it is important to add that the DS-L1 criterion also allows using alternative approaches for the determination of the angle of roll due to the effect of waves. In this respect, reference is made to the procedures in MSC.1/Circ.1200 (IMO, 2006), and the determination of the roll angle is directly linked with the wave steepness to be used in the assessment. As a basis, for standard conditions, the reference wave steepness table is the standard one in the DS-L1 criterion, which corresponds to a standard wind speed of $V_w = 26m/s$. However, if the reference wind speed is modified to reflect operational limitations, Table 2 can be used to redefine the relation between wave steepness and roll period. Such redefined relation can eventually be used within the framework of the procedures specified by MSC.1/Circ.1200 (IMO, 2006). Therefore, also in this context, the specification of a modified reference wind speed V_w is sufficient to embed the effect of operational limitations.

Finally, with reference to the relation between the calculation wave steepness and the ship natural roll period, it is noteworthy to highlight an important difference between the Weather Criterion in the 2008 IS Code (IMO, 2022b) and the DS-L1 criterion in MSC.1/Circ.1627 (IMO, 2020). In fact, the Weather Criterion in the 2008 IS Code (IMO, 2022b) explicitly allows the modification of the wind pressure for ships in restricted service, but it does not explicitly allow the modification of the wave steepness table. This situation in the Weather Criterion in the 2008 IS Code (IMO, 2022b) is a heritage from IMO Res. A.749(18) (IMO, 1993) and, before, IMO Res. A.562(14) (IMO, 1985), despite a corresponding procedure for the modification of the wave steepness table was available in the Japanese domestic standards long before (Yamagata, 1959). It is further noted that a similar situation appears also in the severe wind and rolling criterion for fishing vessels in the Torremolinos Convention (IMO, 2022c), which is based on IMO Res. A.685(17) (IMO, 1991). This has been resolved by the DS-L1 criterion in MSC.1/Circ.1627 (IMO, 2020), as §2.2.2.5 therein explicitly allows the modification of the relation between the calculation wave steepness and the ship natural roll period.

3. Embedding operational limitations in DS-L1 criterion

3.1. Development of the methodology

From the reported background, it is clear that both the pressure P and the relation between wave steepness s and natural roll period T_r can be linked to a common parameter, i.e. the assumed reference wind speed V_w.

Therefore, the implementation of operational limitations can be performed by properly specifying a modified reference wind speed V_w, reflecting the environmental data associated with the considered operational limitations. The specification of a modified reference wind speed leads to a corresponding direct and straightforward modification of the calculation parameters of the DS-L1 criterion, keeping the original theoretical/semi-empirical background of the standard criterion. The standard criterion is of course recovered for a wind speed corresponding to the standard value of 26 m/s.

This concept is not novel, because this idea is essentially the idea at the basis of the framework of the Japanese Stability Standards for passenger ships as described by Yamagata, 1959 and in SLF 51/4/1-Annex 1 (IMO, 2008a). However, as anticipated, in the Japanese standards, the reference wind speed to be considered is limited to three fixed values, corresponding to three ship categories, depending on the ship navigation area, namely, 15 m/s for Coasting-II, 19 m/s for Coasting-I, and 26 m/s for Ocean-going.

Furthermore, this idea is applied also in the framework of the Weather Criterion by the Maritime & Coastguard Agency for UK categorized waters (MCA, 2020). Specifically, for UK categorized waters, the wind pressure and the wave steepness table are modified in accordance with a reference wind speed of 15 m/s, exactly as for the previously mentioned Coasting-II category (Yamagata, 1959; IMO, 2008a).

This background indicates that the idea of modifying the reference wind speed, keeping the structure of the DS-L1 criterion, could be a viable option for regulatory purposes. This approach appears to be reasonable, at least for the time being, also in view of the interim nature of the guidelines in MSC.1/Circ.1627 (IMO, 2020).

However, in the framework of MSC.1/Circ.1627 (IMO, 2020), the implementation of operational limitations should be based on the actual environmental conditions considered in the calculations. Therefore, the use of pre-defined categories and/or wind speeds (Yamagata, 1959; IMO, 2008a; MCA, 2020) is not really in line with the overall framework of second generation intact stability criteria.

Therefore, it is necessary to devise a methodology for directly deriving the wind speed V_w starting from the environmental conditions associated with the considered operational limitations. In this respect, ideally, the statistics of wind speed should be used. However, the framework in MSC.1/Circ.1627 (IMO, 2020) focuses principally on wave statistics rather than wind statistics. This main focus on waves may be linked to the fact that wind effects are accounted for only in case of calculations for the dead ship condition, while the other failure modes are addressed considering only waves.

MSC.1/Circ.1627 (IMO, 2020) provides standard environmental conditions for the calculations. The standard environmental conditions are provided in the form of a reference wave scatter table of significant wave height and zero-crossing period, which is actually taken directly from IACS Rec.34 (IACS, 2001).

When standard DS-L2 calculations are carried out, the following deterministic relation between significant wave height H_s [m] and mean wind speed V_w [m/s] is assumed:

$$V_w = \left(\frac{H_s}{0.06717}\right)^{\frac{2}{3}} \tag{8}$$

The relation (8) comes from an analytical fitting (see IMO (2009)) of the tabular relation between mean wind speed and significant wave height as provided by Umeda et al. (1992) (see also Francescutto et al. (2004)). The original tabular data by Umeda et al. (1992) reflect the indications in the World Meteorological Organization (WMO) Beaufort scale (see, e.g., WMO (2019)).

However, it is also worth noting here that MSC.1/Circ.1627 (IMO, 2020) indicates that relation (8) may be modified when considering alternative environmental conditions.

A graphical representation of the relation (8) between mean wind speed V_w and significant wave height H_s is shown in Fig. 2.

Therefore, although MSC.1/Circ.1627 (IMO, 2020) does not focus specifically on the statistics of mean wind speed, it implicitly embeds a tool for circumventing this limitation. In fact, a deterministic relation between H_s and V_w like relation (8) allows to address the problem using, equivalently, the statistics of H_s or the statistics of V_w. From a statistical perspective, the availability of the statistics for H_s from the wave scatter table, and the availability of the relation (8), means that the statistics of V_w is actually implicitly available by simple transformation of random variables.

Such transformation of variables can be carried out starting from, e.g., the relation between respective cumulative distribution functions (*cdf*), i.e.

$$cdf_{H_s}(H_s) = cdf_{V_w}(V_w(H_s)) \tag{9}$$

It is noted that relation (9) makes use of the fact that the relation (8) is monotonically increasing.

The idea proposed here for defining the wind speed V_w to be used in DS-L1 calculations, is to refer to the mean wind speed with a specific probability of exceedance Pr_{OL}. This probability of exceedance, however, needs to be set.

For reasons of internal regulatory consistency, Pr_{OL} is determined as the probability of exceedance of the standard mean wind speed $V_w = 26m/s$, considering the standard environmental conditions from MSC.1/Circ.1627 (IMO, 2020), and using the relation (8) from DS-L2 criterion.

To determine Pr_{OL}, the distribution of H_s has been determined using the standard wave scatter table from MSC.1/Circ.1627 (IMO, 2020). The obtained probability of exceedance has been interpolated, on log-scale, at a significant wave height $H_s = 8.905m$, which is the significant wave height corresponding to $V_w = 26m/s$ on the basis of (8). The resulting

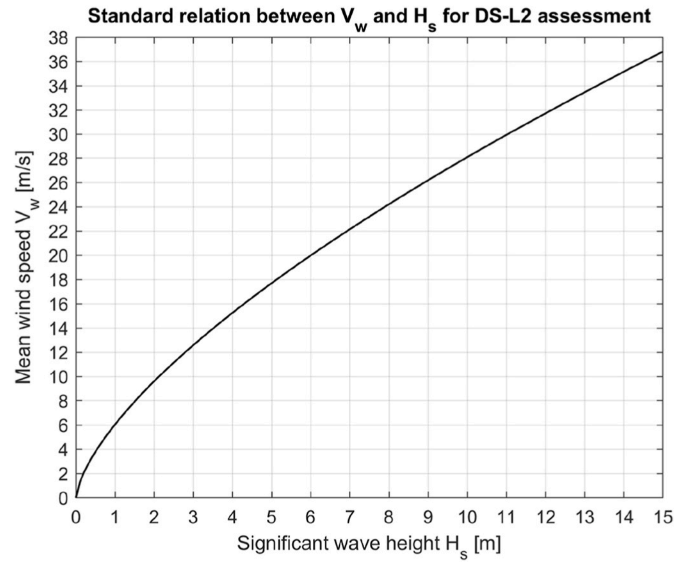

Fig. 2. Standard relation between mean wind speed V_w and significant wave height H_s for DS-L2 assessment according to MSC.1/Circ.1627 (IMO, 2020).

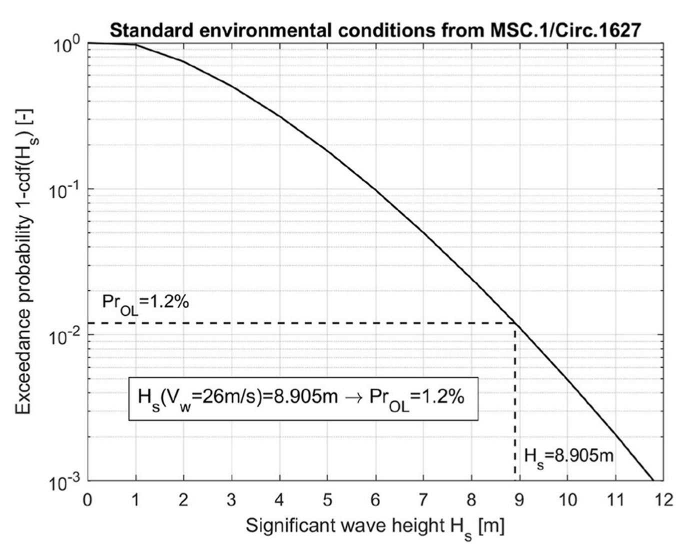

Fig. 3. Determination of reference probability of exceedance Pr_{OL}, using standard environmental conditions from MSC.1/Circ.1627 (IMO, 2020).

reference probability of exceedance is $Pr_{OL} = 1.2\%$, as shown in Fig. 3.

As a result, the devised procedure for embedding operational limitations in the DS-L1 criterion is very simple, and it can be summarised, in general, as follows:

1) Specify the statistics of environmental conditions associated to operational limitations;
2) Determine the reference mean wind speed V_w as the mean wind speed with exceedance probability $Pr_{OL} = 1.2\%$;
3) Calculate the wind pressure P using (6);
4) Determine the wave steepness s at the ship natural period T_r using Table 2;
5) Apply the DS-L1 criterion with modified parameters P and $s(T_r)$.

It is noted that, when the mean wind speed V_w and the significant wave height are linked by a deterministic monotonically increasing relation like (8), the step 2) reported above can be equivalently carried out with reference to the exceedance probability of mean wind speed or significant wave height. When the probability of exceedance of the significant wave height is used at an intermediate stage, as done in Fig. 3, the obtained significant wave height with probability of exceedance Pr_{OL} is finally transformed back to the corresponding mean wind speed. This may be expected to be a common situation because, as already said, the framework of MSC.1/Circ.1627 (IMO, 2020) focuses mostly on wave statistics rather than on wind statistics. In fact, this would actually be the situation when the user has directly at disposal wave statistics, but not wind statistics.

The corresponding procedure, in this latter case, can be summarised as follows:

1) Specify the statistics of environmental conditions associated to operational limitations;
2) Determine the reference significant wave height H_s as the significant wave height with exceedance probability $Pr_{OL} = 1.2\%$;
3) Determine the corresponding reference mean wind speed V_w using (8);
4) Calculate the wind pressure P using (6);
5) Determine the wave steepness s at the ship natural period T_r using Table 2;
6) Apply the DS-L1 criterion with modified parameters P and $s(T_r)$.

As a note regarding internal regulatory consistency, when the described procedure is applied to the standard environmental conditions in MSC.1/Circ.1627 (IMO, 2020), the standard DS-L1 criterion is recovered.

3.2. Some regulatory considerations

The approach devised in section 3.1 allows determining a reference wind speed for DS-L1 assessment, starting from a given distribution of wind speeds or, as could be expected to be more common, from a given distribution of significant wave heights.

The direct result of the application of the approach in section 3.1 is a reference wind speed for DS-L1 assessment under operational limitations. This speed can also exceed the standard wind speed of 26 m/s, depending on the considered environmental conditions. As a result, in principle, the embedding of operational limitations can also lead to calculation parameters that are more severe than standard calculation parameters.

From a conceptual point of view, this can be considered legitimate. In fact, if a specific operational area is particularly severe, and if a vessel operates only in that area, then it is physically sound to consider calculation parameters that are more severe than standard ones.

However, from a regulatory point of view, the situation is more subtle. In fact, the text of MSC.1/Circ.1627 (IMO, 2020) seems to indicate that calculation parameters under operational limitations can be modified, but without becoming more stringent than standard parameters.

In particular, as mentioned also in the previous sections, MSC.1/Circ.1627 (IMO, 2020) indicates that:

- "The value of P used for ships with operational limitations […] may be reduced." (§2.2.2.2 therein);
- "Alternative means for determining the wind heeling lever, l_{w1}, may be used […]. The wind velocity used in the tests should be 26 m/s […]. The value of wind velocity used for ships with operational limitations […] may be reduced." (§2.2.2.3 therein).

It can be seen that, according to MSC.1/Circ.1627 (IMO, 2020), both the reference wind velocity and the pressure, "may be reduced".

This seems to indicate that, in case a reference wind speed associated with operational limitation is found to be larger than 26 m/s, then it should be limited to 26 m/s. If the standard formulation for the pressure P is used, this automatically guarantee that the value of the pressure does not exceed the standard value of 504 Pa (see (6)). In case alternative means of assessment are used, this is not necessarily guaranteed because the calculation pressure depends on the combination of aerodynamic and hydrodynamic effects. Nevertheless, in general, it seems that, according to MSC.1/Circ.1627 (IMO, 2020), the calculation pressure to be used under operational limitation should not exceed 504 Pa.

The situation is fuzzier in case of the calculation steepness. In fact, §2.2.2.5 in MSC.1/Circ.1627 (IMO, 2020) prescribes that:

- "For ships subject to operational limitations […] the wave steepness, […] may be modified."

Therefore, MSC.1/Circ.1627 (IMO, 2020) indicates that the wave steepness factor "may be modified", which is a different wording compared to "may be reduced" used for wind speed and pressure. Therefore, reading the text strictly, the calculation wave steepness under operational limitation may also be increased compared to that associated with unrestricted service.

It is unclear whether the different wording was strictly intended, or whether the effect of the use of a different wording was possibly overlooked, under, perhaps, the implicit assumption that embedding operational limitations should lead always to less stringent calculation parameters.

From the point of view of internal regulatory consistency, if the wind speed and the wind pressure are prescribed to be limited to the standard values of 26 m/s and 504 Pa, respectively, then it would seem reasonable to apply the same approach also for the definition of the modified table of wave steepness, irrespective of the different wording used in the text.

These aspects are associated with a regulatory interpretation of MSC.1/Circ.1627 (IMO, 2020). They have been highlighted in this section for the sake of completeness of the discussion and to highlight that some specific interpretation is likely needed in that respect for uniformity of application.

4. Example applications

This section presents two example applications of the methodology devised in section 3.1. The first example provides a detailed application for a case where the vessel operation is assumed to be limited to the Mediterranean Sea. In the second example, reference average wind speed and corresponding pressure are determined for different areas worldwide. The scope of the second example is to assess how the devised procedure may impact the calculation parameters for different areas of operation.

As a general comment applicable to both the following examples, it is important to note that results of implementation of operational limitations are influenced by the choice of the source of environmental data (see, e.g., the study by Bulian and Orlandi (2022)). Therefore, this should be borne in mind when considering the outcomes from the presented example applications.

4.1. Ship operation limited to the Mediterranean Sea

The first example application of the described procedure is carried out considering the case of ship operation limited to the area of the Mediterranean Sea. According to MSC.1/Circ.1627 (IMO, 2020), this would correspond to a case of operational limitations related to a specified area.

To specify the environmental conditions for the Mediterranean Sea in this example, reference was made to data from Global Wave Statistics Online (BMT, 2022). Data for west (Area 26) and east (Area 27) Mediterranean Sea have been used, considering data for all-year/all-directions. To have a wave scatter table that can be considered to be representative for the whole Mediterranean Sea, the wave scatter tables for Area 26 and Area 27 have been averaged. A map of the two considered geographical areas is reported in Fig. 4.

The mean wind speed and the significant wave height are assumed to be related by (8), i.e. the standard relation from the DS-L2 criterion. As a result, the mean wind speed associated with probability of exceedance Pr_{OL} can be determined after an intermediate step making reference to the exceedance probability of the significant wave height, as described in section 3.1.

The exceedance probability for the significant wave height H_s was derived from the reference averaged wave scatter table. Then, according to the devised procedure, the probability of exceedance has been linearly interpolated, on log-scale, at a value $Pr_{OL} = 1.2\%$, leading to a corresponding significant wave height $H_s = 5.73\ m$. The associated reference wind speed, based on the relation (8) from the DS-L2 criterion, corresponds to $V_w = 19.4\ m/s$. Finally, the wind pressure to be used in the DS-L1 criterion, embedding the considered operational limitations, can be determined from (6) as $P = 281\ Pa$. The whole procedure is summarised in Fig. 5.

The wave steepness to be used in the application of the DS-L1 criterion, embedding operational limitations, can be determined directly from Table 2, using the ship natural roll period T_r and the wind speed $V_w = 19.4\ m/s$ for the calculation of the wave age at natural roll period, β_r. Equivalently, Table 2 can also be transformed into a relation between wave steepness s and natural roll period T_r, using the determined reference wind speed for the considered operational area. This relation

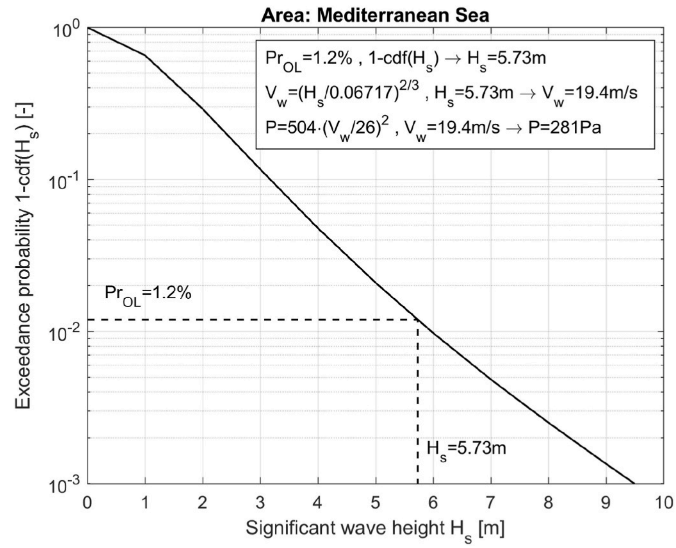

Fig. 5. Mediterranean Sea - Exceedance probability for the significant wave height and determination of reference wind speed. Background environmental data from BMT (2022).

Table 3
Mediterranean Sea - Calculation parameters for level 1 vulnerability criterion for the dead ship condition, assuming operational limitations. Reference wind speed: $V_w = 19.4$ m/s. Background environmental data from BMT (2022).

Natural roll period, T_r [s]	Wave steepness factor, s [-]
≤4.5	0.100
5.2	0.098
6.0	0.093
9.0	0.065
10.4	0.053
11.9	0.044
13.4	0.038
14.9	0.032
16.4	0.028
17.9	0.025
19.4	0.023
20.9	0.021
≥22.4	0.020

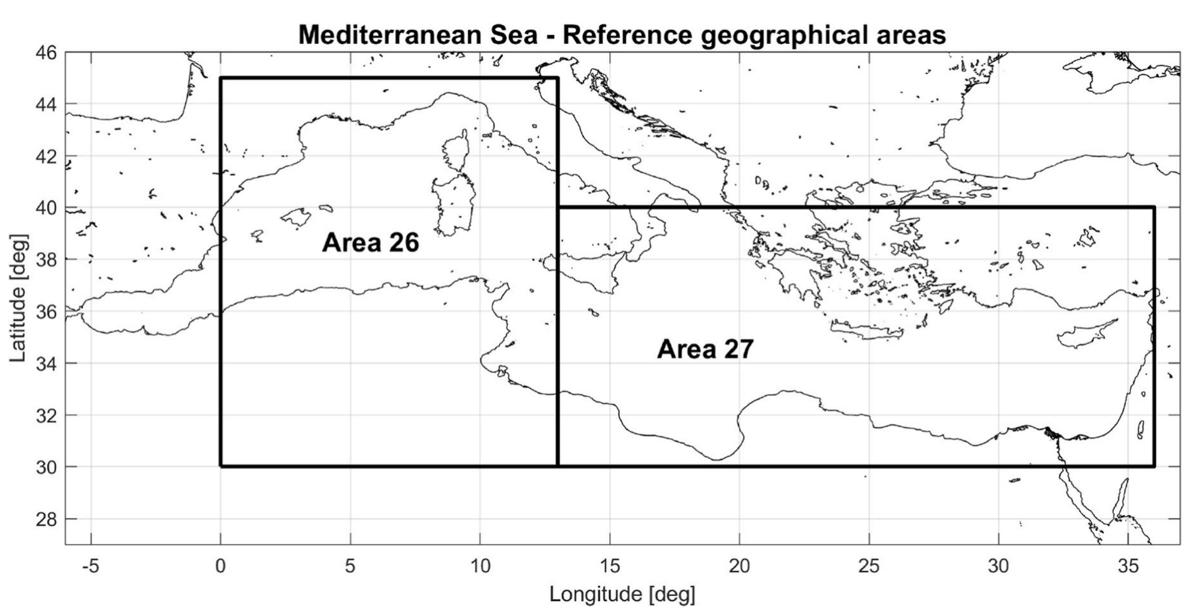

Fig. 4. Considered geographical areas for the Mediterranean Sea region.

is reported in Table 3.

For the sake of completeness, and for ease of comparison, the relation between wave steepness factor s and natural roll period T_r for the unrestricted case and for the case of operations limited to the Mediterranean Sea are reported in Fig. 6.

Finally, it is noteworthy that wave scatter tables in Global Wave Statistics Online (BMT, 2022) have been originally derived from the processing of voluntary visual observations of wind speed and wave height. The processing was based on the NMIMET procedure (BMT, 2022), where wind data play a primary background role. Conversely, the starting point in this example application has been the distribution of significant wave height, and the wind speed exceeded with probability Pr_{OL} has been determined by assuming a relation between wind speed and significant wave height according to DS-L2, i.e. the relation (8). As previously discussed, this may be expected to be a common situation, because criteria in MSC.1/Circ.1627 (IMO, 2020) mostly focus on waves, while wind plays a role only for the dead-ship condition failure mode. Therefore, it may be expected that the users have at disposal wave statistics, but they may not have readily at disposal corresponding wind statistics. As a result, the reported procedure aims at recovering the distribution of wind speed starting from the distribution of significant wave height. Of course, this transformation is, in general, a simplified approximate one. At the same time, the use of the relation between wind speed and significant wave height from DS-L2 (see (8)) can be considered appropriate in terms of regulatory consistency in the frame of MSC.1/Circ.1627 (IMO, 2020) and it can be easily implemented in practical applications. Nevertheless, with specific reference to the case of data from Global Wave Statistics Online (BMT, 2022), using (8) is not equivalent to the original NMIMET analysis (BMT, 2022).

4.2. Determination of reference wind speed and pressure for geographical areas worldwide

In this example application, the reference wind speed V_w and the corresponding pressure P are determined for different geographical areas worldwide. The scope of this application is to provide an example assessment of the variability of the calculation parameters for DS-L1 depending on the operational area of the ship.

Information on environmental data are based on DNVGL-RP-C205 (DNVGL, 2017), which provides information for different geographical areas worldwide, corresponding to the geographical areas from Hogben et al. (1986). A map of the considered geographical areas is shown in

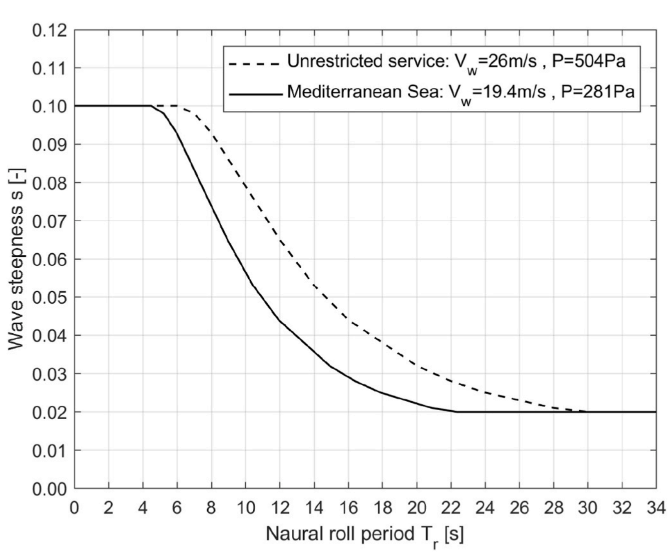

Fig. 6. Comparison of wave steepness as function of natural roll period for unrestricted service and for operation limited to the Mediterranean Sea. Background environmental data for Mediterranean Sea from BMT (2022).

Fig. 7.

For the scope of this example application, the reference information gathered from DNVGL-RP-C205 (DNVGL, 2017) has been the distribution of significant wave height for each geographical area.

In DNVGL-RP-C205 (DNVGL, 2017), the distribution of significant wave height is modelled through a Weibull distribution, with parameters depending on the geographical area. Accordingly, the probability of exceedance of significant wave height for each geographical area can be expressed as follows:

$$P_{exc}(H_s|\text{Area}) = 1 - cdf(H_s|\text{Area}) = \exp\left(-\left(\frac{H_s}{\alpha_s}\right)^{\beta_s}\right) \quad (10)$$

The values of parameters α_s and β_s are provided in DNVGL-RP-C205 (DNVGL, 2017), for each area.

Starting from (10), the procedure in section 3.1 can be directly applied. In fact, setting a probability of exceedance equal to Pr_{OL} according to the procedure in section 3.1, the corresponding reference significant wave height $H_{s,OL}$ can be determined as:

$$H_{s,OL} = \alpha_s \cdot (-\log(Pr_{OL}))^{\frac{1}{\beta_s}} \quad (11)$$

Afterwards, the reference wind speed V_w can be obtained from $H_{s,OL}$ using (8). Finally, the reference pressure P can be obtained from V_w using (6).

Results of the calculations are reported in Table 4. The calculated wind speed was rounded to one decimal digit and, for consistency, the pressure was calculated from the rounded wind speed. For a limited set of areas, identified by an asterisk in Table 4, the calculated wind speed exceeds 26 m/s and, correspondingly, the pressure exceeds 504 Pa, i.e. the standard values in the DS-L1 criterion (in this respect, see the discussion in section 3.2). It is noted that the North Atlantic region in IACS Rec.34 (IACS, 2001) corresponds to the combination of areas 8, 9, 15 and 16, while the Mediterranean Sea can be represented by the combination of areas 26 and 27.

A graphical representation of the results in Table 4 is shown in the form of maps in Figs. 8 and 9, for the wind speed and for the pressure, respectively.

The obtained results indicate the following range of reference wind speed and pressure across all the considered area:

$$\begin{cases} 14.7 \le V_w[m/s] \le 27.9 \\ 161 \le P[Pa] \le 580 \end{cases} \quad (12)$$

It is noteworthy that the obtained range is close to the range of wind speeds and corresponding pressure in the Japanese Stability Standards for passenger ships as described by Yamagata, 1959 and in SLF 51/4/1-Annex 1 (IMO, 2008a): 15 m/s and 168 Pa for Coasting-II, 19 m/s and 269 Pa for Coasting-I, and 26 m/s and 504 Pa for Ocean-going. Furthermore, the ranges of wind speed and corresponding pressure become almost identical in case the reference wind speed is limited to 26 m/s (see section 3.2).

The wind speed obtained for each geographical area can then be used for the determination of the calculation wave steepness for given ship roll period (see Table 2 and section 3.1). As a result, either the dimensionless Table 2 is used for calculations, or, equivalently, one table of wave steepness depending on the roll period can be obtained for each geographical area.

For ease of interpretation of the obtained results, the relation between wave steepness and natural roll period has been determined for a set of representative wind speeds in the obtained range (see (12)), and results are shown in Fig. 10.

Data shown in Fig. 10 clearly indicate that the introduction of operational limitations can have a significant impact on calculation parameters in DS-L1 assessment, depending, of course, on the considered operational area.

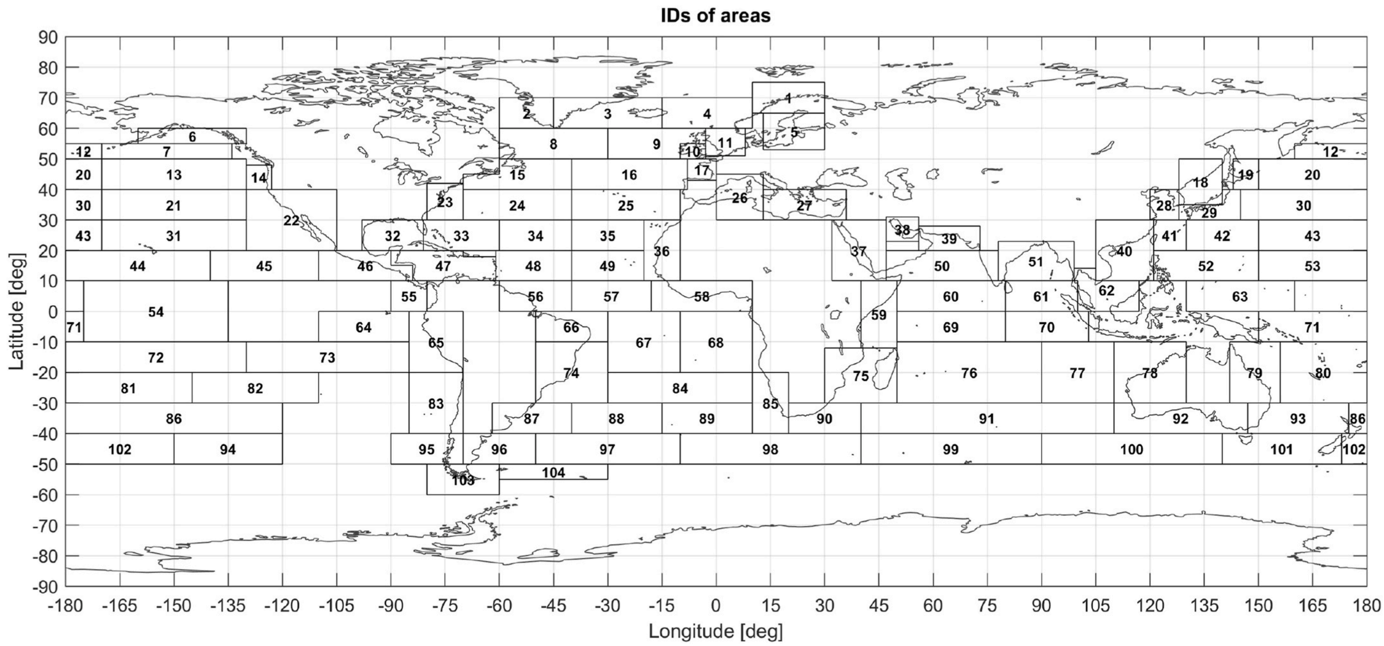

Fig. 7. Geographical areas for data from DNVGL-RP-C205 (DNVGL, 2017).

Table 4
Reference wind speed V_w and corresponding pressure P for each geographical area. Areas identified by an asterisk are associated with wind speed larger than 26 m/s and pressure larger than 504 Pa. Background environmental data from DNVGL-RP-C205 (DNVGL, 2017).

Area	V_w [m/s]	P [Pa]	Area	V_w [m/s]	P [Pa]	Area	V_w [m/s]	P [Pa]	Area	V_w [m/s]	P [Pa]
1	22.4	374	*27*	18.9	266	*53*	18.9	266	*79*	19.4	281
2	19.9	295	*28*	19.5	284	*54*	17.3	223	*80*	20.2	304
3	24.7	455	*29*	21.7	351	*55*	15.0	168	*81*	21.6	348
4	23.2	401	*30*	24.5	448	*56*	17.1	218	*82*	20.2	304
5	16.5	203	*31*	20.0	298	*57*	15.9	188	*83*	19.7	289
6	23.6	415	*32*	17.6	231	*58*	14.7	161	*84*	19.8	292
7	24.1	433	*33*	18.4	252	*59*	17.0	215	*85*	22.4	374
*8**	26.1	508	*34*	19.8	292	*60*	19.1	272	*86*	23.5	412
*9**	26.1	508	*35*	19.2	275	*61*	17.1	218	*87*	22.2	367
10	22.7	384	*36*	18.3	250	*62*	17.8	236	*88*	23.9	426
11	22.4	374	*37*	16.2	196	*63*	16.5	203	*89*	25.0	466
12	25.4	481	*38*	15.5	179	*64*	16.9	213	*90*	25.3	477
13	24.0	429	*39*	18.0	242	*65*	16.3	198	*91*	25.4	481
14	22.7	384	*40*	21.6	348	*66*	16.9	213	*92*	24.5	448
15	24.9	462	*41*	21.4	341	*67*	17.1	218	*93*	23.0	394
16	25.9	500	*42*	21.4	341	*68*	17.3	223	*94**	26.9	539
17	24.1	433	*43*	20.9	326	*69*	17.5	228	*95*	24.2	437
18	20.2	304	*44*	19.1	272	*70*	18.2	247	*96*	22.7	384
19	23.1	398	*45*	18.5	255	*71*	16.0	191	*97**	26.2	512
20	25.4	481	*46*	17.6	231	*72*	18.3	250	*98*	25.1	470
21	22.5	377	*47*	18.4	252	*73*	18.6	258	*99**	27.0	544
22	18.7	261	*48*	17.7	234	*74*	18.6	258	*100**	27.9	580
23	21.1	332	*49*	17.8	236	*75*	21.2	335	*101*	24.8	459
24	24.3	440	*50*	21.2	335	*76*	21.3	338	*102*	23.8	422
25	22.8	388	*51*	17.7	234	*77*	21.8	354	*103**	26.2	512
26	19.3	278	*52*	19.5	284	*78*	20.5	313	*104*	23.5	412

5. Conclusions

The framework of second generation intact stability criteria in MSC.1/Circ.1627 introduced the possibility of embedding so-called "operational limitations". When operational limitations are introduced, standard environmental conditions are substituted by specific environmental conditions, and this substitution generally reflects on the calculation parameters of the criteria.

From a conceptual perspective, this idea can be found also in, e.g., the weather criteria in the 2008 IS Code and in the Torremolinos Convention for fishing vessels, but with a lack of corresponding standardized application procedures, and with partial consideration for the specific operational conditions of the ship.

The framework of MSC.1/Circ.1627 brings the link between design and operation to a new level, strengthening the connection between safety-by-design and safety-by-operation. In this context, MSC.1/Circ.1627 provides systematic and standardized methodologies for the implementation of operational considerations in the intact stability assessment. This is an important novelty compared to the existing regulatory framework, because it potentially allows a tailored design based on the envisioned operation of the ship, with a more uniform application.

Information is available for implementing operational limitations for most of the failure modes and levels of assessment. However, this is not

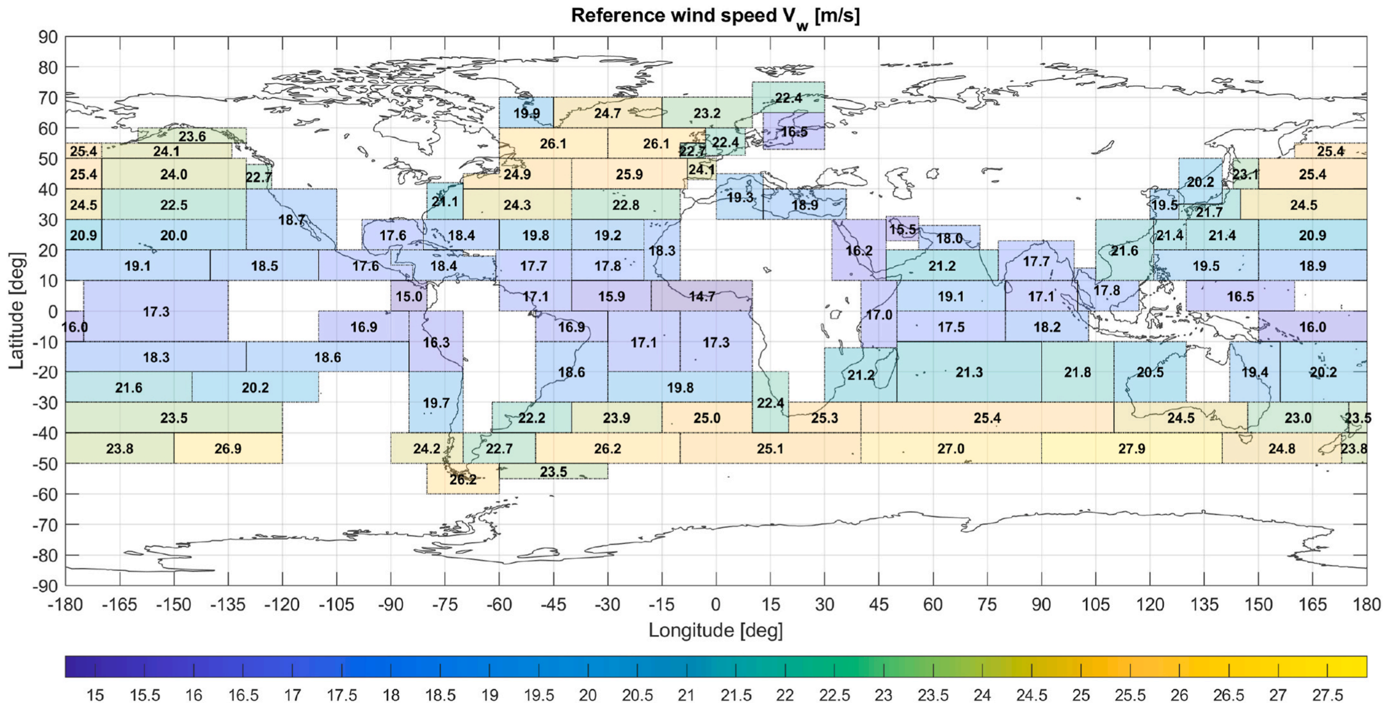

Fig. 8. Geographical distribution of reference wind speed V_w. Background environmental data from DNVGL-RP-C205 (DNVGL, 2017).

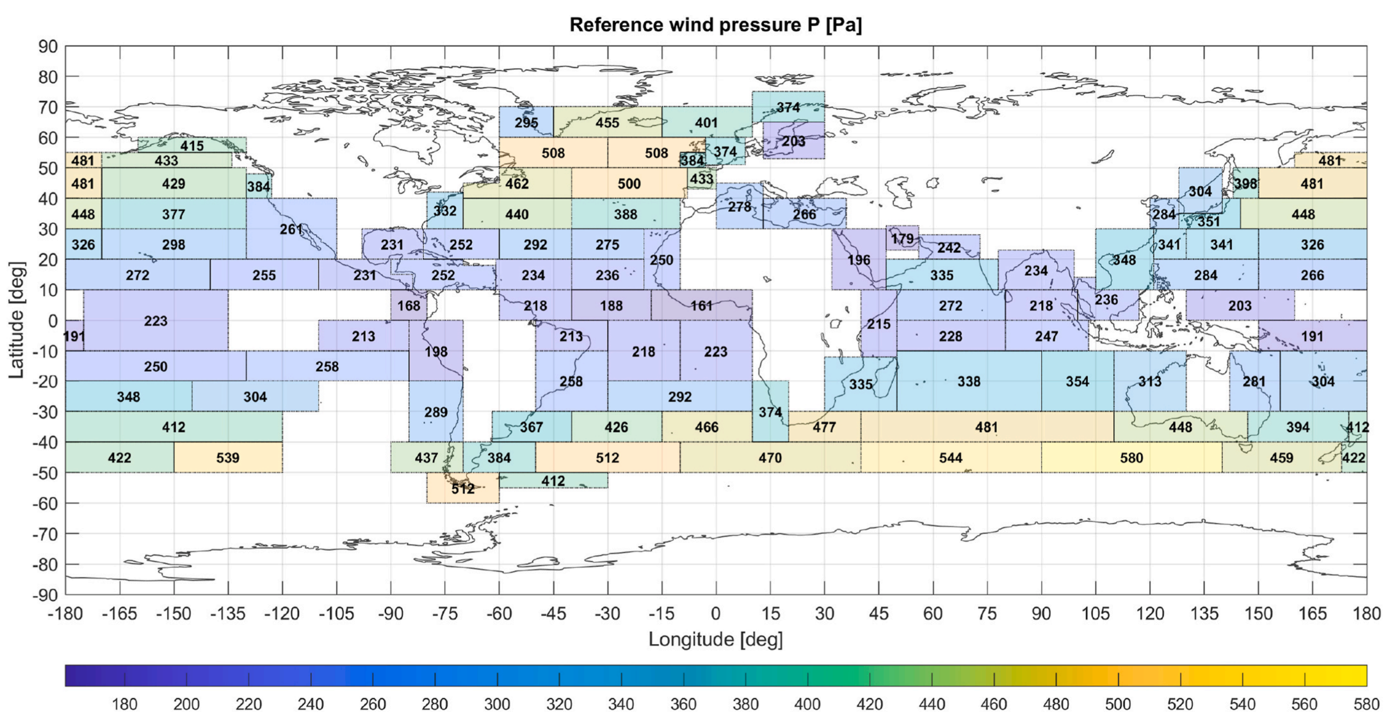

Fig. 9. Geographical distribution of reference pressure P. Background environmental data from DNVGL-RP-C205 (DNVGL, 2017).

the case for the level 1 vulnerability criterion for the dead ship condition, for which relevant information are missing both in MSC.1/Circ.1627 and in the corresponding Explanatory Notes. It is also noted that, according to MSC.1/Circ.1627, operational limitations for the dead ship condition failure mode can be implemented only in the form of limitations related to areas or routes and season.

Therefore, the paper has investigated the development of a rational simple procedure for contributing filling this gap. The proposed approach leverages on the fact that the level 1 vulnerability assessment criterion for the dead ship condition is based on the Weather Criterion, and on the fact that approaches already exist in some regulatory frameworks for the modification of the wind speed, of the wind pressure and of the wave steepness table of the Weather Criterion.

The proposed methodology is based on the idea of re-defining the reference wind speed under operational limitations as the mean wind speed associated with a given probability of exceedance based on long-term statistics of environmental conditions.

This probability of exceedance has been determined as $Pr_{OL} = 1.2\%$

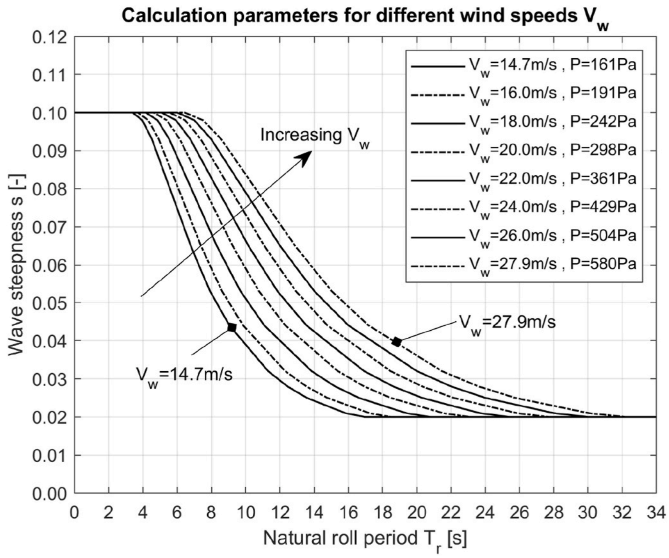

Fig. 10. Calculation parameters for different wind speeds.

by reasoning based on the standard environmental conditions in MSC.1/Circ.1627, and by exploiting the deterministic relation between significant wave height and mean wind speed that is assumed as standard relation by the level 2 vulnerability criterion for the dead ship condition.

In principle, the long-term distribution of wind speeds can be used to determine the reference wind speed under operational limitations. However, the framework of MSC.1/Circ.1627 mostly focuses on waves rather than wind. Therefore, it may be expected that a common application of the described approach could be based on the analysis of distribution of significant wave heights, with a subsequent calculation of the reference wind speed. Specifically, from the distribution of significant wave height for a given operational area, the reference significant wave height is determined as the significant wave height with exceedance probability Pr_{OL}. Subsequently, the reference wind speed is determined from an assumed deterministic relation between significant wave height and mean wind speed.

The subsequent steps are independent of the approach followed for the determination of the reference wind speed, i.e. either directly through distribution of wind speed or through the distribution of significant wave height. In fact, once the mean wind speed is re-defined on the basis of the considered operational limitations, the calculation parameters of the criterion associated with the environmental conditions, namely the wind pressure and the wave steepness table, can be correspondingly determined. Eventually, the modification of the calculation parameters reflects the operational limitation in the application of the criterion.

The implementation of the proposed methodology is straightforward, and two example applications have been presented. In the first one, a detailed example application is shown for a case where the vessel operation is assumed to be limited to the Mediterranean Sea. In the second example application, reference average wind speed and corresponding pressure have been determined for different areas worldwide. This latter example was aimed at assessing how the devised procedure may impact the calculation parameters for different areas of operation. The obtained results clearly indicate that the introduction of operational limitations can have a significant impact on calculation parameters in DS-L1 assessment, depending, of course, on the considered operational area.

It is finally noteworthy that the proposed approach can be considered to be relevant also for the case of level 1 vulnerability assessment for the excessive acceleration failure mode. In fact, the corresponding criterion shares the same wave steepness table as the level 1 criterion for the dead ship condition, and also for the level 1 criterion for excessive acceleration failure mode there is no specific information on how to embed operational limitations, neither in MSC.1/Circ.1627 nor in the corresponding Explanatory Notes. At the same time, it is important to underline that the application scheme for operational measures in case of excessive acceleration failure mode is different from that for dead ship condition failure mode. In fact, for the case of excessive acceleration failure mode, the full spectrum of operational measures (i.e. both operational limitations and operational guidance) can be applied, whereas this is not the case for the dead ship condition failure mode. This is a consequence of the substantial difference between the assumptions behind the assessment for excessive acceleration and for dead ship condition failure modes. In fact, differently from the case of dead ship condition, for the case of excessive acceleration failure mode, the ship is considered to be fully operational. Therefore, regarding operational limitations for the excessive acceleration failure mode, implementation is possible in terms of areas or routes and season, like for the dead ship condition failure mode, and also in terms of maximum significant wave height, which, instead, is not possible for the dead ship condition failure mode.

Credit author statement

Gabriele Bulian: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Alberto Francescutto: Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study and that are not subject to sharing restrictions are available from the corresponding author, upon reasonable request.

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