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ON THE ESTIMATION AND APPLICATION OF DIRECTIONAL DESIGN CRITERIA

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ABSTRACT

This article discusses the estimation of directional metocean design criteria for engineering applications. We provide a summary of current code recommendations relating to directional design criteria and illustrate conceptually and mathematically some of the difficulties of their derivation. We also discuss the application of directional criteria for the specific examples of Code Check and Pushover analyses for fixed structures and jack-up rigs.

1. INTRODUCTION

The use of directional metocean design criteria for the analysis of offshore structures is sometimes motivated by the opportunity to reduce perceived conservatism associated with the use of omni-directional criteria. In truth, no such conservatism exists, since by definition an omni-directional return value represents that value which has the target annual probability of exceedance from all directions combined. Furthermore, reducing the return value from one or more directions without a compensatory increase in the return value from at least one other sector can only increase the probability of failure of the structure above the target value and hence decrease its reliability below what is intended.

To motivate the current work, we first summarise recommendations concerning the use of directional design criteria given in design codes and highlight the inconsistencies and lack of clarity in those codes. We then give intuitive explanations for how we might specify directional design criteria rationally, with mathematical detail provided in a supporting annex. In particular, we describe circumstances in which some benefit can properly be derived from the use of directional criteria. The arguments presented are relevant for application to: (a) the design of new fixed structures; (b) the re-analysis of existing structures, both in terms of Code Check and Pushover analyses; and (c) site-specific assessments of jack-ups. In the context of the last of these, the logic that is presented is also extended to the use of seasonal criteria. Each of the types of application is dealt with explicitly in the sections below. It is appreciated that the loading on fixed jackets tends to be dominated by the largest individual maximum wave and that current and wind also play a part. Similarly, for jack-ups the wind-loading can sometimes be the critical factor with wave and current contributing. However, for illustrative purposes to demonstrate the logic, the paper focusses on a single indicative parameter, significant wave height, *Hs*, as an indicator of structural loading but the generality of the argument means that it can be applied to any type of environmental variable.

Whilst the reasoning also applies to the design and analysis of floating structures, those are not dealt with specifically in this paper but will be left to a future publication.

2. NOMENCLATURE

CDF	Cumulative Distribution Function
CNS	Central North Sea
EVA	Extreme value analysis
Hs	Significant wave height
MODU	Mobile Offshore Drilling Unit
RSR	Residual Strength Factor
TEWL	Tide + surge + wave crest

3. DIRECTIONAL CRITERIA IN ENGINEERING STANDARDS

The main current international engineering standards for metocean criteria and their application to fixed structures and jack-ups are listed in Table 1. The main metocean standards are ISO 19901-1 [1], DNVGL-RP-C205 [2] and API RP 2MET [3] and these are the first port of call for the metocean engineer in the oil and gas industry. The authors advocate the overall approach outlined in these three documents. The key statements in these standards are all based on Forristall [4] which presents a sound statistical basis for the derivation and use of directional extremes in the context of fixed jackets. Superficially, at least these three standards are therefore in agreement in the sense that they all require that the *composite* probability of exceedance of a set of directional extremes be consistent with the omni-directional equivalent. However, illustrative of the lack of consistency and clarity is that the actual values presented in API RP-2MET [3] Section C.4.9.2.2.4, for example, do not appear consistent with the advocated method since the factors that are provided to scale omni-directional values are all less than unity. As will be described below, this cannot provide a set of directional extremes consistent with the aspiration of "the overall reliability of the structure not …[being] … compromised by the use of such lower directional environmental conditions."

In terms of engineering standards, ISO 19902:2007 [5] is an example where the method described to determine directional extremes relates more to the traditional approach of scaling up criteria which is in contradiction to the method described above. Whilst NORSOK N-003 [6] is in broad agreement with the latter, it presents a formulation which seems to be related to the use of a return period based on half the number of sectors. ISO 19905-1 [7] allows for the use of directional criteria but does not provide any guidance as to how those criteria should be derived nor does it guide the reader towards any other document for assistance.

Given the general lack of clarity in this area and the presence of inconsistencies between or even within standards, the authors felt that some explanation of the statistical theory behind the ISO 19901-1 [1] approach would be beneficial. We also describe some of the difficulties in deriving directional criteria and attempt to provide practical ways of applying rational statistically-sound approaches for different engineering applications. Hopefully, this will help metocean engineers to be able to derive directional extremes in a consistent, defensible manner and allow engineers to understand and apply appropriate criteria for specific engineering applications.

4. STATISTICAL BACKGROUND

This section outlines the basic statistical premise of the approach described in the metocean standards which leans heavily on the Forristall [4] approach and gives some hypothetical examples to help illustrate the key points.

4.1 Definition of a return value

For application to the analysis of offshore structures, the definition of a return value is: *The severity of a parameter that would be expected to be exceeded once in the corresponding return period*. In the context of omni-directional significant wave height, Hs, therefore, the 100-year value, Hs_{omni}^{100}, is the level that would be expected to be exceeded once in 100 years irrespective of direction. Whilst it is true some directions are more likely to see that event than others, all sectors in general contribute to the *probability* of exceedance for the event - the omni-directional CDF is an aggregate of the CDFs from all directional sectors. This is a key characteristic of the omni-directional distribution, that it incorporates effects from all directional sectors and therefore is strictly linked (in a clear statistical sense) with the individual independent directional sectors. For further mathematical explanation, see the Annex.

Traditionally, omni-directional extremes have been derived by combining all directional sectors at the start of the analysis by putting all storm peaks into a single pot and applying a single EVA to the whole population. In many cases, this can be hard to justify since different directional sectors generally have different probability distributions, so combining them into a single analysis is theoretically unsound. Using this approach also masks the fact that the omni-directional probability distribution is made up of these different populations. The current authors and co-workers have published numerous articles in recent years [9,10,11] describing a method whereby the distribution of the N-year omni-directional maximum is explicitly derived by combination of distributions for contributing directional sectors. Using this approach, mathematical relationships between directional sectors and omni-directional extremes becomes much clearer.

Below are some hypothetical examples which explore the relationship between exceedance probabilities of storm peaks in individual direction sectors, considered independent at this stage, and exceedance probabilities for the combined, omni-directional case.

4.2 Example 1 - Homogeneous Environment, Equal Storm Occurrence Rate

In this example, the environment is completely homogeneous from all directions in terms of both the severity of storm peaks and their rate of occurrence. In this case, the Hs_{omni}^{100} is just as likely to come from one direction as any other.

We could decide to split the analysis into two directional sectors as illustrated in Figure 1. In this case, half the peaks would come from the northerly sector and half from the south. Given that the two sectors are equal and that half the storms occur in each sector, the 200-year extreme from each direction sector is identical to the 100-year omni-directional extreme – essentially, the storm occurrence rate in each sector has been halved from the omni-directional case, so the return period for the same Hs return value has to be doubled

Table 1 Directional criteria in engineering and metocean standards

Standard	Application	Section	Statement
ISO 19901-1:2015	Metocean design and operating considerations	5.6	" … the overall reliability of the structure is not compromised by the use of such lower directional environmental conditions"
DNVGL-RP-C205	Environmental conditions and environmental loads	3.6.5.3 – 3.6.5.5	"3.6.5.3 If directional information is used in a reliability analysis of a marine structure, it is important to ensure that the overall reliability is acceptable. There should be consistency between omnidirectional and directional distributions so that the omnidirectional probability of exceedance is equal to the integrated exceedance probabilities from all directional sectors. 3.6.5.4 The concept of directional criteria should be used with caution. If the objective is to define a set of wave heights that accumulated are exceeded with a return period of 100-year, the wave heights for some or all sectors have to be increased. Note that if directional criteria are scaled such that the wave height in the worst direction is equal to the omnidirectional value, the set of wave are still exceeded with a return period shorter than 100-year. 3.6.5.5 A set of directional wave heights that are exceeded with a period TR can be established by requiring that the product of non-exceedance probabilities from the directional sectors is equal to the appropriate probability level."
API RP-2MET (2014)	Derivation of Metocean Design and Operating Conditions API RP 2A-WSD (2018) refers reader to API RP-2MET	A.5.6	"Where directional variations of parameters are used, the sectors should generally not be smaller than 45°. In the environmental conditions should be scaled up such that the combined event from all sectors has the same probability of exceedance as the target return period, see Reference [12] (FORRISTALL, G.Z., On the use of directional wave criteria, J. Waterway, Port, Coastal and Ocean Engineering, 2004)."
		C.4.9.2.2.4	"The extreme waves provided are omni-directional. Directional extreme waves for return periods greater than 10 years and for water depths greater than 30 m can be approximated by factoring the omni-directional value using Figure C.23." However, the values stated are not compatible with the essence of Section A.5.6
ISO 19902:2007	Petroleum and natural gas industries - Fixed steel offshore structures	9.4.2	"When directional data are used, directional sectors should generally not be smaller than 45°. The environmental conditions should be scaled up such that the most severe sector is no less severe than the omni-directional 100 year condition"
NORSOK N-003_2017	Action and Action Effects	6.1.4	"When using directional metocean criteria for obtaining characteristic actions or action effects, it shall be verified that they fulfil requirements regarding target annual exceedance probabilities. If omni-directional extremes are used for all sectors, no correction effects apply. The directional metocean condition actually used shall result in actions fulfilling overall requirements regarding annual exceedance probabilities. The most accurate approach is to perform a full long-term analysis, i.e. the exceedance probability is estimated for each direction and the resulting probability is taken as a weighted sum of the directional failure probabilities. The weights are the directional probability of incoming metocean conditions. Such an analysis will show that for some sectors, the design metocean condition need to be artificially adjusted in order to give adequate design actions when a long-term analysis is not carried out. A characteristic directional wave height can be calculated as the wave height corresponding to an exceedance probability of q/(0,5), where q is the number of directional sectors (e.g. for 12 sectors, the 10^{-2} extreme value for each direction corresponds to the 600 year return period). The characteristic wave height for a given sector is taken as the minimum of calculated equivalent characteristic wave height and the omni-directional characteristic wave height. In principle, this correction method also applies to wind and current."
ISO 19905-1 (2016)	Site-specific Assessment of Mobile Offshore Jack-up Units	6.4	"Omnidirectional data can be sufficient but, in particular circumstances, directional data can also be required."

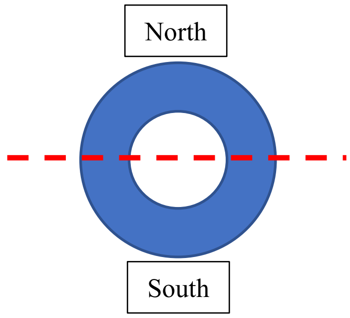

Figure 1 Splitting analysis into two equal directional sectors

In mathematical terms, the annual probability of exceedance of Hs_{omni}^{100} and Hs_{dir}^{200} are given by:

$$P(Hs_{omni}^{100}) = \frac{1}{100} \tag{1}$$

$$P(Hs_{north}^{200}) = P(Hs_{south}^{200}) = \frac{1}{200} \tag{2}$$

and therefore:

$$P(Hs_{north}^{200}) + P(Hs_{south}^{200}) = P(Hs_{omni}^{100}) = \frac{1}{100} \tag{3}$$

Note that equation (2) neglects second order and higher effects, as explained in Annex A. For return periods of 100 years or greater the impact of this approximation is very small.

In this case, the combination of the independent 200-year directional extremes from north and south therefore have the same probability of exceedance as the 100-year omni-directional extreme. Similarly, if the environment were to be split into 4 equal sectors, it is clear that the independent directional extreme for each sector, Hs_{dir}^{400}, would be equivalent to Hs_{omni}^{100} and the equivalent of equation 3 for this case would be:

$$P(Hs_{north}^{400}) + P(Hs_{east}^{400}) + P(Hs_{south}^{400}) + P(Hs_{west}^{400}) = P(Hs_{omni}^{100}) = \frac{1}{100} \tag{4}$$

The mathematical derivation of this result is also given in the Annex. The key feature here is that *the summation of the probability of exceedance of the two (or four) sectors is equal to the probability of exceedance of the omni-directional case.* In other words, there is a very precise statistical relationship between the exceedance probabilities of independent individual sectors and the exceedance probability of all sectors combined (the omni-directional case) and this holds for unequal as well as equal sectors. This illustrates that an arbitrary selection of directional sectors does not affect the overall exceedance probability. Clearly, it wouldn't make any sense if you could just increase the number of sectors for your analysis and end up with lower return values as a result.

4.3 Example 2 - Homogeneous Environment, Unequal storm Occurrence Rate

Let us assume in the next case that the CDF is the same from each sector, but the occurrence rate is 4 times as high from the south as from the north. In this case, the probability of exceedance for the omni-directional return value is different for each sector only due to the different storm occurrence rates. If we again want to make a set of 100-year directional return values that are equal from each direction, we would have the following set of exceedance probabilities:

$$P(Hs_{north}^{500}) + P(Hs_{south}^{125}) = P(Hs_{omni}^{100}) = \frac{1}{100} \tag{5}$$

$$\frac{1}{500} + \frac{4}{500} = \frac{5}{500} = \frac{1}{100} \tag{6}$$

Here we are adding the 500-year annual exceedance probability from the north and the 125-year exceedance probability from the south and in combination, these again produce an omni-directional probability of exceedance of 1/100. In relation to the omni-directional case, the southerly sector has a storm occurrence rate that is 4/5 that of the omni-directional value and so for the same return value the return period has to be increased by 5/4, from 100 years to 125 years. Similarly, for the northerly sector, the storm occurrence rate is 1/5 of the omni-directional rate, so the return period is increased by 5 times to produce the same return value.

Of course, we could still decide to take the 200-year directional return values from each sector, as in case 1, and present those as a valid combination that has the same probability of exceedance as Hs_{omni}^{100}. In this case, although the probability of *exceedance* from each sector would be the same, the *return values* would be different. The northerly return value would decrease (from the 500-year return value) and the southerly value would increase (from the 125-year return value). This in turn would mean that although the northerly sector would now be lower than Hs_{omni}^{100}, the southerly return value would be larger. The mathematical reasoning for this result is given in the Appendix.

This illustrates that although directional extremes can be defined for a set of values that has the same probability of exceedance as the omni-directional case from every sector, if you decrease the value from one direction you have to increase the value from another. In effect, you are robbing Peter to pay Paul.

4.4 Example 3 – Directionally-varying Environment and Storm Occurrence rate

In real cases, there is much more variability between sectors in terms of storm severity and storm occurrence rate, but the principles outlined above still hold. In most real cases, the omni-directional return value has a different probability of exceedance from each sector. So, for example, in a 4-sector case in which Hs_{omni}^{100} is 14m and in which this *Hs* has the following annual probability of exceedance from each of the four sectors:

North	= 1/1200
East	= 1/600
South	= 1/200
West	= 1/400

With reference to equation (4) we now have:

$$P\left(Hs_{north}^{1200}\right) + P(Hs_{east}^{600}) + P\left(Hs_{south}^{200}\right) + P(Hs_{west}^{400})$$

$$= P\left(Hs_{omni}^{100}\right) = \frac{1}{100} \quad (7)$$

or

$$\frac{1}{1200} + \frac{1}{600} + \frac{1}{200} + \frac{1}{400} = \frac{1}{100} \quad (8)$$

If the probability of exceedance (and hence the return period) from any of these sectors were to be reduced, the corresponding omni-directional exceedance probability would reduce also. The sum in (8) can only remain the same by increasing the return period (and return value) from another sector. This means that using directional extremes does not decrease the overall probability of exceedance, it just moves the probabilities around from one sector to another. It is analogous to squeezing a balloon, where squeezing some parts of the balloon inwards inevitable results in other parts of the balloon squeezing outwards between your fingers.

The omni-directional extreme is not therefore a conservative solution; it is just a special case where all sectors have the *same return value*. The other special case, for an 8-sector example, as described in Forristall [4] is where all sectors have the *same probability of exceedance*, i.e. 1/800. It should be emphasized though that these are just two special cases of directional extremes and in fact, there are an infinite number of combinations of directional values which can sum to produce the same omni-directional probability of exceedance. As mentioned above though, in any combination that we come up with, any reduction below Hs_{omni}^{100} in one or more sectors has to be balanced by an increase in at least one other sector above the 100-year omni-directional value.

4.5 Traditional Derivation of Directional Criteria

In the past, directional and omni-directional return values were derived separately. Extrapolative uncertainty notwithstanding, the return values in all sectors individually must extrapolate to a lower value than the omni-directional return value for the same return period since the omni-directional extreme is the aggregation of the directional effects. The only exception to this is when only one sector is completely dominant, and all other sectors have a completely negligible contribution to the omni-directional extreme. One example of this would be waves off Nigeria, where southern-ocean swell is the only source of large wave events.

Traditionally, once the omni-directional and independent directional extremes had been derived, a ratio was determined between the former and the largest directional sector return value. That ratio was then used to scale all independent sectors up to produce a composite set of sectoral extremes. As stated earlier, though, if some sectors are below the omni-directional value and none are higher this inevitably results in a lower composite probability of exceedance than in the omni-directional case. It should also be noted that scaling all sectors up by the same amount destroys the statistical relationship between the individual sectors and the omni-directional case, so the resultant composite probability of exceedance is impossible to know *a priori*.

4.6 Comparison between Approaches

Table 2 presents an indicative summary of annual exceedance probabilities for a 4-sector case based on different analysis approaches. The first column represents the traditional approach in which the composite annual probability of exceedance is somewhat below 1/100. Typically, it tends to come out as somewhere around 1/20 and 1/50 but will vary on a case-by-case basis. The second column represents a case where the return value from each sector is the same (and equal to the omni-directional value) but the probability of exceedance is different, and the composite annual probability of exceedance is equal to the target value of 1/100. The third column represents the other special case where the annual probability of exceedance from each sector is the same, but return values are different, and once again the composite probability is equal to target. The final column illustrates the combination of the 100-year independent values from each sector for completeness.

It should be emphasized that there are strict statistical relationships between the values in the second, third and fourth columns. The traditional approach in the first column does not have that strict relationship and the composite value is not generally calculated.

Table 2 Illustrative composite return periods using different analysis approaches

	Scaled-up Traditional approach	Omni-directional from all sectors	Equal Prob. of Exc.	100-year from each sector
North	1 / 100	1 / 1200	1 / 400	1 / 100
East	1 / 500	1 / 600	1 / 400	1 / 100
South	1 / 150	1 / 200	1 / 400	1 / 100
West	1 / 300	1 / 400	1 / 400	1 / 100
Composite	**1 / 45**	**1 / 100**	**1 / 100**	**1 / 25**

5. APPLICATION CASES

In the context of the reliability of fixed jacket structures, global collapse is generally dominated by extreme individual waves. Traditionally, the metocean criteria for this sort of application have been based on the "scaled-up" approach which in reality yields an indeterminate composite event probability. The approach advocated in ISO 19901-1 [1] is to use a set of directional extremes which together combine to the same composite probability of exceedance as the omni-directional case from all direction sectors. To recap, there are an infinite number of these but with two special cases: (a) the omni-directional case from every direction sector which is characterized by the same wave height from each sector, and (b) the same return period from every direction sector with an annual probability of *1/[n * RP]*, where RP is the target return period and there are *n* sectors. Two questions spring to mind: (a) How do we reconcile the infinite number of possible combinations of directional metocean extremes with a single set of delivered metocean criteria? and (b) how do we select the optimum set of directional extremes from the infinite number of possibilities? These questions have been discussed to some extent in Jonathan [9] and Forristall [4] and this is explored further here, again using *Hs* as an indicator of environmental severity.

5.1 Design of New Structures

New structures are in general designed against omni-directional extremes, so the directionality question is of little relevance. However, if directionality were to be used, then there would indeed be an infinite number of ways that the structure could be built. Optimally, it would make sense perhaps to make the structure stronger in those directions where the environment is more severe and weaker in others. Figure 2 illustrates this in a case where the loading from the 100-year environment (suitably scaled for safety factors) is represented by the red dots and three different ways of resisting the loading are illustrated by the blue dashed lines. In effect here, we have an infinite number of ways of resisting the loading and the one with the lowest overall cost might be considered optimal. To follow this route, some sort of iterative approach would probably be needed to optimise the design.

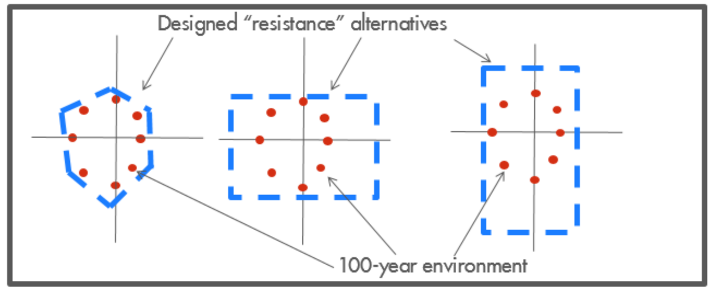

Figure 2 Illustration of ways of designing a platform to resist the environment

5.2 Analysis of Existing Structures

For existing structures that are being re-analysed there is clearly not as much flexibility as you would have for designing an as-yet unbuilt structure. Re-assessment is typically needed on a regular basis to ensure that a structure continues to meet the reliability targets in the light of actual changes to the structure (e.g. more topsides weight, additional caissons, corrosion); better understanding of the strength of the structure or foundations; or, changes in or improved understanding of the extreme metocean conditions. In any of these cases, the first stage of the re-analysis process is typically to carry out a Code Check. If it fails, then a more detailed and time-consuming Pushover analysis is performed to determine the actual return period of failure. Both of these approaches are described in the following sections.

5.3 Code Check

The Code Check methodology uses a component level approach as a relatively quick way to determine whether a structure has sufficient strength for the target reliability. Typically, both the 100- and 10,000-year metocean conditions are applied to the structure using a linear analysis, using software such as SESAM. Standard Code Check formulae are used to estimate the strength of the individual members and joints. The formulae are identical for all checks, but the reference loads and load factors associated with each return period will vary. The resistance of the structure is determined via the interaction of the axial and bending loads in each member and joint and any over-utilisations of components are identified. In this linear analysis no redundancy between members is factored in: we simply identify whether components are over-utilised or not. The result is therefore a pass/fail for each trial case.

Effectively, therefore, if the 100-year directional return values are used with the appropriate load factors and the analysis passes, the inference is that the structure is better than the 100-

year target from that direction sector. However, implicitly, the probability of failure is related to the combined probability of failure from each sector and when the directional sectors are combined all we know is that the structure is better than the composite probability of exceedance of the individual sectors. This puts us into a world, where we need to know that this *composite* probability of exceedance is better than the target return period and so we need to produce a set of metocean conditions that also has an appropriate composite probability of exceedance as described in the previous section. If the directional return scaling-up approach had been used to derive the criteria, we wouldn't know what the composite probability of exceedance was, but we would know that it was less than the 100- or 10,000-year targets.

Therefore, for a Code Check analysis, a set of directional extremes needs to be selected which in composite has an annual probability of exceedance of 1/100 (or 1/10,000). As indicated above, there is no definitive set of these and any set that we produce is in effect just a guess at a set which passes. An illustration of the sort of process that might be required to find a solution is provided in the succession of plots in Figure 3. In each of these plots, the large blue circle represents the normalised (suitably factored) resistance of a structure in each directional sector. The coloured dots represent a composite set of directional loading extremes. The green dots represent the loading from those directions where the suitably-factored load is less than the resistance (and hence would be a pass in the Code Check) and the red dots represent cases where the loading is higher and so represent a "fail". The composite probability of exceedance of the dots in all 3 attempts is the same.

Attempt 1 represents a first guess at a set of conditions that would pass the Code Check and may represent tabulated metocean criteria provided to a structural engineer. However, in this case, the attempt would fail because although 4 of the sectors pass (SW, W, NW and N) there are four directions where the loading exceeds resistance, as indicated by the 4 red dots.

The metocean engineer may then produce a second set of criteria as depicted in Attempt 2 in which the metocean conditions (and hence load) from the sectors that passed the check have been increased slightly and those in the "red" sectors reduced. The guesses from Attempt 1 are now shown as open circles and the direction of change towards the values for Attempt 2 are indicated by the arrows – red arrows indicating an increase of severity and the green arrows a decrease. In this case, the changes have only resulted in a reduction of the number of non-compliant sectors from 4 to 3. Therefore, a further attempt may be made in which the severity from the 3 sectors that failed in Attempt 2 are further reduced and the increases required to keep the composite probability of exceedance the same are apportioned between the SW and W sectors. On this occasion, the Code Check would now pass as indicated by all the filled dots now being green.

It is worth noting here that although the third attempt does pass, it isn't a unique solution, and that is evident because there is still some spare capacity in some directions, i.e. N, NE, E, SE, SW and NW where the green dots are slightly inside the blue circle. However, it does show that if we can find at least one solution that works, the structure as a whole must be strong enough for the target reliability. The less spare capacity there is, of course, the harder it would be to find a combination that worked and in cases where there was insufficient capacity, no solution would be possible.

In this particular case, it took 3 attempts to reach a suitable combination but clearly, in the case of a structure where the loading route is complex and affects a large number of joints and members it may be difficult to know exactly which way to make each of the adjustments. Whilst it is relatively quick to run a linear analysis of this type as typically all directions and combinations can be assessed in a single run it can still be problematic to find a directional set which does satisfy the requirements. Therefore, in practice, if a plausible directional combination fails, it is usual to then go to the next level of complexity, which is a Pushover analysis. This approach is also generally performed where a structure only narrowly passes a Code Check, since the simplified linear analysis is not sufficiently complex to capture the non-linearities and redundancies in a real structure.

5.4 Pushover Analyses

If the Code Check either fails or is thought to be insufficient to demonstrate that the structure is reliable enough a more sophisticated non-linear Pushover analysis is carried out (using a tool such as USFOS) which takes into account structural redundancy and load-shedding of specific components. In this approach, there is a defined Residual Strength Factor (RSR) target which is dependent upon the return period being tested, i.e. 100 or 10,000 years. Generally, the metocean conditions for one or both of these return periods are applied with the crest height from the largest direction set at the total extreme water level, *TEWL*, by adjusting the still water depth (related to tide and surge). This depth is then used for the analysis from all directions. The load vectors at each depth are then ramped up until "global collapse". In this context, global collapse is defined as the load at which the substructure can carry no additional loading.

For a non-redundant structure this would occur on first member failure but for a redundant structure there can be multiple member, joints or pile failures prior to ultimate collapse. For example, in a redundant jacket, framing braces can buckle and shed load into adjacent bracing, which can continue to carry additional load until overall failure of the frame. Individual piles can also reach capacity and shed load into adjacent piles in a cluster. Once failure has occurred, the ratio of the failure load to the characteristic load is calculated and compared with the

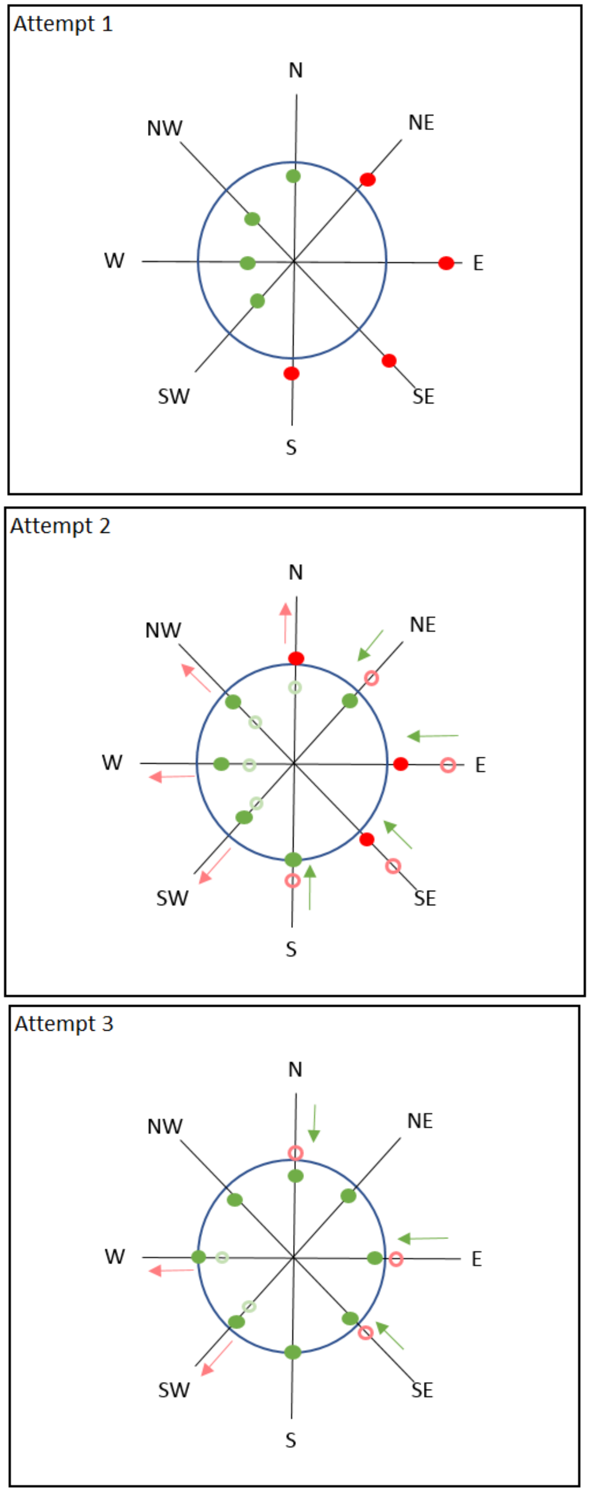

Figure 3 Illustrative progression towards a viable set of composite directional extremes.

target "load factors". Typically, these are 1.85 for the 100-year load case and 1.0 for 10,000 years.

With this approach, a separate non-linear analysis is needed for each case and each run needs some engineer verification to confirm successful completion. The results also need to be interpreted to decide at which load level failure has actually occurred. The return period of the load is usually determined either by a hazard curve approach, wherein the ratio of the 10,000-year to 100-year load is assumed for a particular region, or, by determining the slope of the load curve explicitly by calculating the load for a number of return periods from each direction sector.

Whilst this approach is much more time-consuming than a Code Check it does allow for the actual probability of failure from each direction to be determined with no trial and error. In order to achieve this, the probabilities of failure from each section are combined at the *end* of the analysis to give an overall probability of failure. This differs from the Code Check approach where the probabilities are combined at the start to produce a composite guess at a set of directional criteria which will pass the check. The implication of this is that the 100- and 10,000-year directional return values that should be used for this type of analysis, are the *independent* return values and not a composite set. Thus, when the probabilities are combined to produce an overall probability of failure we are effectively producing a composite set of return values (whose return periods we calculate) that we *know* just cause failure as opposed to the Code Check case, where we select a candidate set of composite return periods and calculate the return values from those which may or may not cause failure of the structure.

5.5 Site-Specific Assessment of Jack-Ups

This application is in many ways similar to that of re-assessment of fixed jacket structures, since the jack-up is already built. There is sometimes flexibility in the heading that can be chosen for the rig, but this is usually very limited due to the presence of other infrastructure and operational considerations. In terms of the probability of failure of the structure, the same statistical arguments apply as for the fixed structure case.

5.6 Seasonal Criteria

Seasonal extremes are often required for jack-ups or other types of MODU, or for structures requiring temporary repairs/mitigations which will only be in place at a particular location for a restricted period. For these cases, similar arguments apply to seasonal and directional criteria.

To illustrate this, let us look at a hypothetical case where a season consists of three months each of which has an exactly equal climate in terms of severity and rate of occurrence of storm peaks. If there were to be a storm occurrence rate of, say 10 storms per month, then for the season as a whole there would be 30 storm events. This in effect means that the 100-year extreme from the whole period would be equal to the 300-year extreme of each month individually. It is therefore not sufficient use the 100-year extreme from each month individually to determine the overall structural risk.

It is certainly true that many regions of the world have significant variations of environmental severity throughout the year and for selected periods which include both summer and winter, the summer months' impact on the overall extremes tends to be negligible. However, for periods which comprise months of comparable severity, such as November to February (in mid and northern latitudes in the northern hemisphere) it is important to recognise that the return values from the combined period will be higher than the extremes for each month individually. As for the directional case, this is because the probability distribution of the overall period has contributions from each of the contributing months and thus will be larger than any of the months individually.

6. THE EFFECT OF DEPENDENCE BETWEEN SECTORS

The arguments given above are based on the assumption of statistical independence between directional (or seasonal) sectors. In reality all storms have some directional variation through their history. Typically, this is captured by taking the maximum *Hs* within each directional sector of interest and adding that point to the population of events before the EVA is carried out. In other, Monte Carlo-type analyses [10], the EVA is performed on just the storm peaks and during the simulation approach a storm dissipation model is used to determine the maximum values in other directional sectors. With either of these approaches, there are two hypothetical extreme cases: (a) Complete independence between sectors: this is achieved where storms dissipate very quickly with direction. In this circumstance, the analysis as described above is relevant; and (b) Complete dependence: this scenario occurs if storm severity decreases negligibly with direction and goes right round the compass, such that every directional sector experiences the same severity from every storm. In this case, if the analysis were to be performed per sector for n sectors, return values from all sectors would be the same and the apparent storm occurrence rate would be n times higher than reality. In this case, treating each sector individually either in a Code Check or Pushover sense would yield highly conservative results.

In practice, most cases will fall somewhere between these two extremes, and the wider the directional sectors are, the closer we get to case (a), that of independent storms. It is usual to define sectors of 45˚ width, and indeed as indicated in Table 1, API RP-2MET recommends that sectors narrower than this not be used. Nevertheless, even with 45˚ sectors there will be some degree of inter-sector dependence. To get some idea about the impact of this dependence, the approach of Feld et al [10] was used to determine 8-sector directional *Hs* return values with and without storm dissipation.

Illustrative directional analyses were carried out based on continuous 3-hourly hindcast data sets for three locations: (a) Norwegian Sea, (b) Central North Sea, and (c) Offshore Brazil. The analysis methodology used was a directional-seasonal analysis using Shell's CEVA software [10] which fits non-stationary generalised Pareto distributions to storm peaks over threshold, and non-stationary Poisson models to storm occurrence rates above threshold. The non-stationary threshold is defined across a 2-D directional-seasonal domain. Monte Carlo analysis (or equivalent) was then used to randomly simulate storm peak events under the fitted model. There is only one storm peak event per (independent) storm, and it occurs in just one directional sector. Hence there is no dependence between return values for storm peaks in different directional sectors.

The directional decay (or dissipation) of a storm relative to its storm peak, and the dependence between directional sectors it causes, must be taken into account for design. This is particularly important in deriving maximum individual wave and crest height statistics for both directional and omni-directional cases, in order to properly capture the effect of storm duration on short-term variability. Normalised directional storm histories of events from the hindcast (time-series of storm severity and direction) were also extracted; these could then be scaled and shifted to match simulated storm peak severity and direction from the Monte Carlo simulation. In this way, simulations of directional time-series of sea-state storm severity are generated, corresponding to any return period of interest. The storm shapes effectively represent the dissipation characteristics of storms and implicitly the level of correlation between extremes of sea state variables in different directional sectors. Not including storm duration and dissipation effects is almost impossible to justify. The statistical dependence between return values for different sectors, and hence a degree of conservatism in the way that directional extremes are combined, might be viewed as a necessary evil in the context of tabulated metocean criteria.

Estimated return values (using both "storm peak" and "dissipated" analyses) for each location are now discussed. The 100-year return values shown are normalised with respect to the 100-year omni-directional value for each location, so as to emphasise the effect of directional dependence. Results are shown in Figure 4 to Figure 6 for the peaks-only and dissipation-included cases. A summary of the percentage increase in the 100-year *Hs* ratios between the two cases are given in Table 3, quantifying the impact of storm dissipation on the directional extremes. Whilst there are different ways of determining storm dissipation which are likely to produce some variation in the extent of the impact, values of the same order would be expected.

Table 3 Illustrative percentage increase per directional sector, of including storm dissipation on 100-year Hs return values. Shading indicates severity of sectors.

	Norwegian Sea	CNS	Brazil
N	5	3	7
NE	12	2	12
E	11	2	12
SE	4	3	6
S	12	4	5
SW	1	6	2
W	2	2	1
NW	4	0	4

From this admittedly small collection of locations the following characteristics seem common: (a) The impact of dissipation tends to be more pronounced for the less severe sectors – in these, the dissipated tails of storms that peak in other sectors make a significant contribution; (b) The effect on any single sector can be up as high as 12%. However, the two most severe sectors in each location (indicated by the dark shading in the table) are only affected by at most 3% and the 3rd most severe sectors by at most 5%; (c) The size of the effect varies between regions; and (d) From Figures 4-6 we see that the size of the effect tends to be largest at the lower return periods.

The extent of these uplifts is a broad-brush indicator of the correlation between sectors and the effect of assuming sectors are independent; this effect appears to be relatively small, and probably will vary by region and by type of metocean variable. Nevertheless, on balance, deriving extremes based on the assumption of independent directional sectors in the current cases appears to be of less concern compared with looking at storm peaks for estimation of return values for individual waves.

An alternative approach might be to use a structure-variable type method whereby failure (or not) is determined for every time step of a hindcast or simulated time series and therefore the probability of global collapse could be calculated directly. This would require, however, a sufficiently accurate and efficient method to be able to calculate structural failure which also presents significant difficulties of its own.

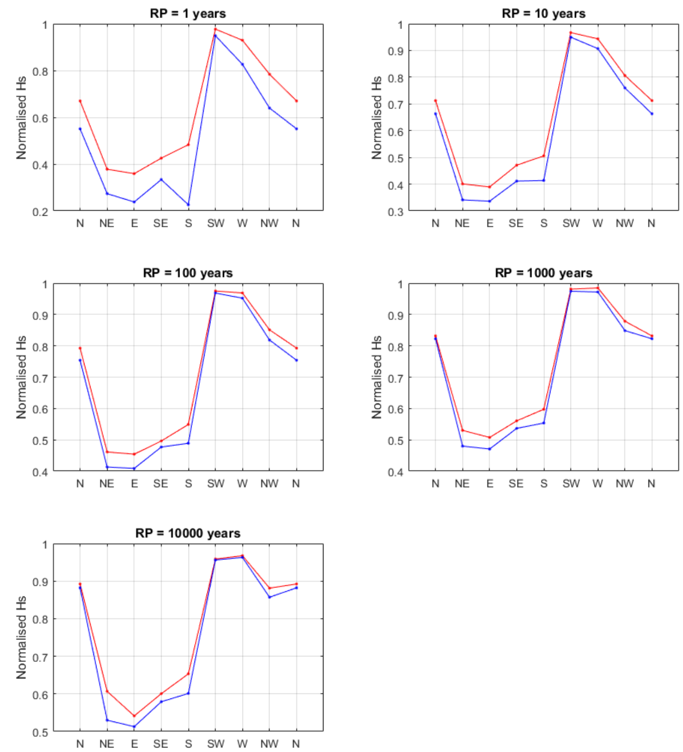

Figure 4 Norwegian Sea - normalised 100-year directional return values for peaks (blue) and with dissipation (red)

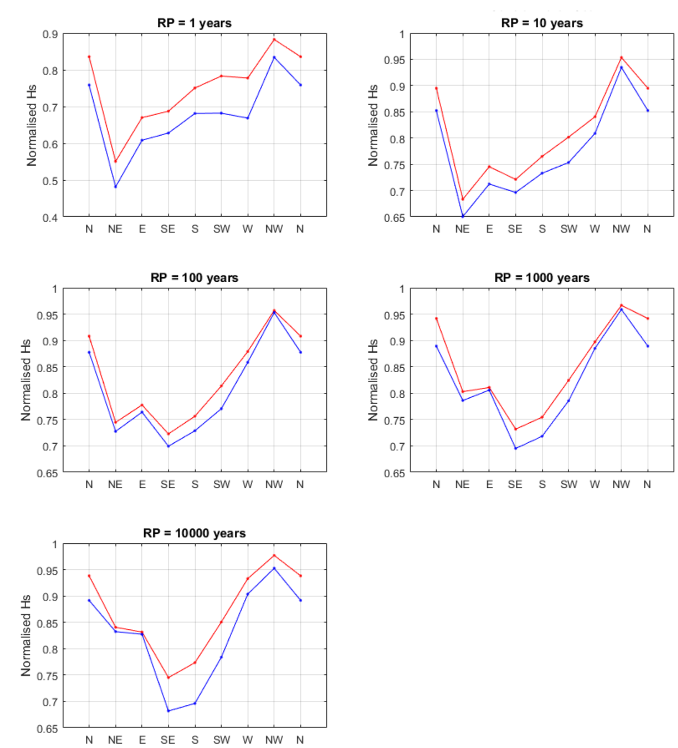

Figure 5 CNS - normalised 100-year directional return values for peaks (blue) and with dissipation (red)

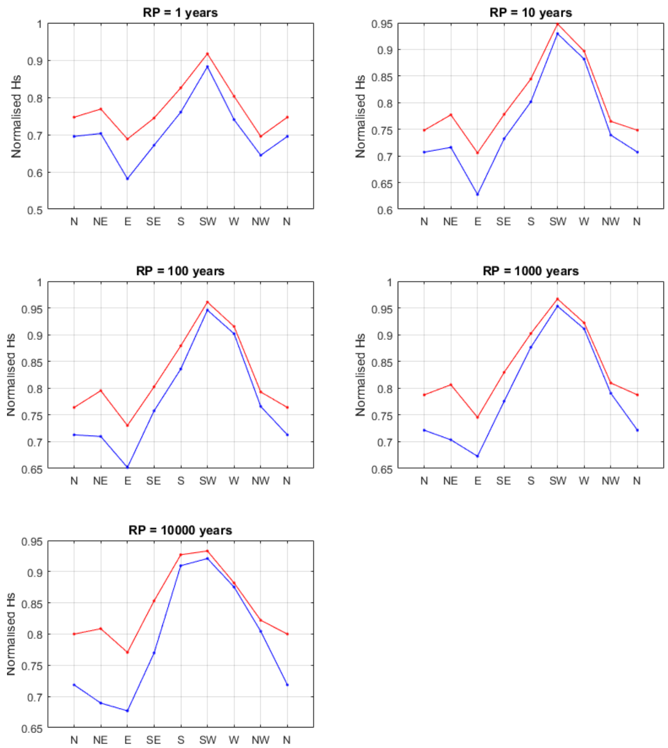

Figure 6 Brazil - normalised 100-year directional return values for peaks (blue) and with dissipation (red)

7. DERIVATION OF METOCEAN CRITERIA

This paper has outlined why omni-directional extremes do not represent overly conservative design and why conversely directional extremes tend to have an apparent level of conservatism in them when used in a manner which assumes that direction sectors are completely independent. The degree of dependence, however, will be case-dependent but in practice, the only way to remove the conservatism completely is to perform omni-directional analyses only or to determine structural loading/failure directly. The former, however, allows for no optimising of a structure to reflect the directional characteristics of the environment and the latter has its own difficulties in terms of the complexity of analysis that is required. In terms of the derivation and application of metocean criteria, the following is therefore offered as a reasonable way forward in order to get the best solutions for different applications. Whilst this does add a level of complexity and requires a greater level of understanding, it also does allow practitioners to get the best result for structures in terms of both safety and efficiency of design. The approach also accepts that there is a certain level of implicit conservatism, but that this is probably small in most cases.

7.1 Tabulated criteria

Providing different sets of tabulated criteria for different applications makes the job of the Metocean Engineer somewhat harder as well as increasing the possibility of mis-use of data. It is important in this scenario, therefore, that both Metocean and Structural Engineers have an understanding of the ideas described in the preceding sections and know how and when to apply the specific sets of criteria involved.

The most usual applications of metocean extremes that have been discussed here are: (a) Omni-directional, all-year extremes for the design of new structures; (b) Independent directional extremes for Pushover analyses; (c) Composite, all-year directional extremes for the re-assessment of existing jackets using a Code Check approach; and (d) Composite directional extremes for different collections of months for the assessment of temporary structures or site-specific assessment of MODUs.

Cases (a) and (b) represent the extreme values that come straight out of the typical Metocean Engineer's extremal analysis and hence require no special manipulation. Cases (c) and (d) require additional manipulation to achieve the composite statistical results that are needed. The next section describes one way of developing criteria for these applications.

7.2 Derivation of Composite Directional Extremes

In Jonathan and Ewans [9] a cost function was presented which could be used to determine the optimum combination of directional extremes. Whilst this is a theoretically reasonable approach, in most cases a cost function is not readily available and/or can be hard to apply to multiple analyses in a straightforward way and therefore some other optimising approach would be necessary. However, the authors have also found in practice, that the use of 800-year criteria is rarely optimal since the largest sector usually increases significantly above the omni-directional extreme and the effect of this increase is much more deleterious than any benefit gained from reductions in other sectors. As a compromise, we now propose an iterative approach which both minimises the amount of increase above the omni-directional return value and also ensures that the composite statistical constraints are still maintained. The main elements of the approach are as follows:

1. Start with the omni-directional return value in all sectors, Hs_{omni}^{100}.
2. Increase the return value from the most severe directional sector by a small amount, Δ_{Hs}.
3. Determine the return period, RP, of $Hs_{omni}^{100} + \Delta_{Hs}$ for that sector.
4. Determine the remaining probability required to give an overall composite probability equal to the target value.

So, for example, if the target return period is 100 years and the *RP* of the largest sector from step 3 were, say 400 years, the consumed annual exceedance probability would be 1/400, leaving 1/100 – 1/400 = 3/400 that could be allocated between the remaining 7 sectors.

5. Set the annual exceedance probability for the remaining sectors as 3/(400 *7) = 3/2800, which is equivalent to a annual probability of exceedance of 933 years. Whilst this is a higher return period than the 800-year solution, this increase is applied to the less severe sectors.
6. Determine the 933-year return values in the 7 remaining sectors.
7. If the largest value from these sectors is no larger than $Hs_{omni}^{100} + \Delta_{Hs}$ then use the resultant combination of extremes.
8. If the largest value is greater than $Hs_{omni}^{100} + \Delta_{Hs}$, set the return value for the second largest sector to also equal $Hs_{omni}^{100} + \Delta_{Hs}$, determine its annual probability of exceedance and apportion the remaining probability to the 6 remaining sectors.
9. If the largest value from these sectors is no larger than $Hs_{omni}^{100} + \Delta_{Hs}$ then use the resultant combination of extremes.
10. Continue the process until a solution is found.
11. If no solution is possible, increase Δ_{Hs} and repeat steps 2 – 10.

It should be noted that whilst this approach does produce a valid set of composite extremes there is no guarantee that this set is optimal for any given structure in any given environment. However, it does produce a set with a minimal increase above the omni-directional return value.

8. RECOMMENDATIONS AND CONCLUSIONS

Since the publication of Forristall [4] there has been some appreciation of the statistical issues related to the derivation and use of directional metocean criteria, albeit poorly understood and inconsistently applied. The 800-year solution is one that has been touted but this is rarely optimal for a structure since it usually results in a significant increase in the worst sector above the omni-directional. However, the 800-year case, and indeed the omni-directional case are just two special cases of an infinite number of combinations that could be used for a Code Check. It is also important to realise that considerations around composite extremes are not relevant for a Pushover analysis since the probabilities of failure are combined at the end of the analysis. For this application, therefore, independent 100-year and 10,000-year directional extremes should be used.

A single optimal combination of metocean criteria can only be determined on a case-by-case basis and with detailed knowledge of the structure to which it is being applied. An alternative method is presented for tabulated metocean criteria which at least has the benefit of having a minimal increase above the omni-directional case and does not require any structural details to determine. The approach does have a small element of apparent conservatism associated with dependence between sectors (as indeed do all methods that determine tabulated metocean criteria) but this is unavoidable unless a structure-variable approach is used to determine the probability of failure directly from a time series (either historical, synthetic or Monte Carlo).

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ANNEX A

STATISTICAL BACKGROUND

Independent directional sectors: Consider a situation with m directional sectors $\{S_i\}_{i=1}^{m}$. Suppose that X_i represents the annual maximum event in directional sector S_i, and that X_o represents the corresponding omni-directional annual maximum (i.e. over all sectors), so that $X_o = \max_i(X_i)$. If the $\{X_i\}$ are independent, then we can relate return values of $\{X_i\}$ with those of X_o as:

$$P(X_o \leq x) = P\left(\max_i\{X_i \leq x\}\right) = \prod_i P(X_i \leq x)$$

We can therefore also relate the omnidirectional non-exceedance probability $p_o = P(X_o \leq x)$ with the corresponding sector non-exceedance probabilities $\{p_i\}$ where $p_i = P(X_i \leq x)$:

$$p_o = P(X_o \leq x) = \prod_i P(X_i \leq x) = \prod_i p_i$$

The T-year omni-directional return value is defined using $P(X_o \leq x) = 1 - 1/T$. Therefore, if we are interested in specifying sector criteria consistent with the T-year omni-directional return value, we can allocate any combination of values for $\{p_i\}$ provided that:

$$p_o = 1 - \frac{1}{T} = \prod_i p_i$$

Equal sector non-exceedance probabilities: One possibility is to insist that each of the p_i take the same value p_*, so that $p_o = p_*^m$ and hence:

$$p_* = p_o^{1/m} = \left(1 - \frac{1}{T}\right)^{1/m} = 1 - \frac{1}{mT} + O(1/(mT^2))$$

That is, in each of the m sectors, we would set $p_i = P(X_i \leq x) = p_* \approx 1 - 1/(mT)$ corresponding to the mT-year return value per sector, as discussed in the main text. So if we have $m = 8$ directional octants, we would need to use the 800-year return value in each octant.

Different sector non-exceedance probabilities: However, there are an infinities number of possibilities to satisfy (in the case of independent sector extremes) the constraint:

$$1 - \frac{1}{T} = \prod_i p_i$$

For example, in the case of $m = 2$ we might use sector return periods T_1 and T_2 such that:

$$\begin{aligned} 1 - \frac{1}{T} = p_1 p_2 &= \left(1 - \frac{1}{T_1}\right)\left(1 - \frac{1}{T_2}\right) \\ &= 1 - \left(\frac{1}{T_1} + \frac{1}{T_2}\right) + O(\frac{1}{T_1 T_2}) \end{aligned}$$

That is, any combination of periods T_1 and T_2 satisfying $1/T = 1/T_1 + 1/T_2$ will suffice, as described in the main text.

Dependent directional sectors: In the case of dependent directional sectors, we have:

$$P(X_o \leq x) = P\left(\max_i\{X_i \leq x\}\right) > \prod_i P(X_i \leq x)$$

The inequality above arises because the random variables $\{X_i\}$ are no longer independent, and hence the cumulative distribution function of their maximum can no longer be written as the product of their cumulative distribution functions. However, we can still demonstrate the effect that sector dependence has on the specification of appropriate sector return values. For example, in the case of equal sector non-exceedance probability, we can write $p_o = p_*^{m_*}$ where m_* is the *effective* number of independent directional sectors, with $m_* \in [1, m]$. The limiting cases are $m_* = m$ (corresponding to independence) and $m = 1$ (complete dependence between sectors). In this case, it would be appropriate to set the sector return values to correspond with the $m_* T$-year return period. In principle, an empirical estimate for m_* can be obtained from a sample of historical data.