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FISHING EFFORT CONTROL REGULATIONS INFLUENCE ON STABILITY, SAFETY AND OPERABILITY OF SMALL FISHING VESSELS: STUDY OF A SERIES OF STABILITY RELATED ACCIDENTS OCCURRED IN SPAIN BETWEEN 2004 AND 2007

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To mi wife / A mi mujer

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GLOSSARY

CDF	Cumulative distribution function
CI	Capsize index
CIAIM	Maritime Accident and Incident Investigations Standing Commission (*Comisión Permanente de Investigación de Accidentes e Incidentes Marítimos*)
CFP	Common fisheries policy
CPISM	Maritime Casualty Investigation Standing Commission (*Comisión Permanente de Investigación de Siniestros Marítimos*)
DGMM	General Directorate for the Merchant Marine (*Dirección General de la Marina Mercante*)
EMSA	European Maritime Safety Agency
EU	European Union
F/V	Fishing vessel
FAO	Food and Agriculture Organization
GM	Transversal metacentric height
GT	Gross tonnage
GRT	Gross register tonnage
GZ	Righting lever
Hs	Significant wave height
SFFR	Spanish fishing fleet register
ILO	International Labour Organization
IMCO	Inter-governmental Maritime Consultive Organization
IMO	International Maritime Organization
INE	National Statistics Institute (*Instituto Nacional de Estadística*)
KG	Height of gravity centre over base line
MAGRAMA	Spanish Ministry for Agriculture, Food and Environment (Ministerio de Agricultura, Alimentación y Medioambiente)
NATO	North Atlantic Treaty Organization
NW	Northwest
OI	Operability index
RAO	Response amplitude operator
RD	Royal Decree
SFFR	Spanish fishing fleet register
SGISC	Second Generation Intact Stability Criteria
SI	Stability index
SLF	IMO Subcomittee on Stability and Load Lines and on Fishing Vessels Safety
Tcap	Mean capsize time
UK	United Kingdom
US	United States
V1	Enclosed volume over main deck
V2	Enclosed volume below main deck

RESUMEN

Entre los años 2004 y 2007 se hundieron por problemas de estabilidad cinco pesqueros españoles de pequeña eslora, de características parecidas, de relativamente poca edad, que habían sido construidos en un intervalo de pocos años. La mayoría de los tripulantes de esos pesqueros fallecieron o desaparecieron en esos accidentes.

Este conjunto de accidentes tuvo bastante repercusión social y mediática. Entre ingenieros navales y marinos del sector de la pesca se relacionó estos accidentes con los condicionantes a los diseños de los pesqueros impuestos por la normativa de control de esfuerzo pesquero. Los accidentes fueron investigados y publicados sus correspondientes informes; en ellos no se exploró esta supuesta relación.

Esta tesis pretende investigar la relación entre esos accidentes y los cambios de la normativa de esfuerzo pesquero.

En la introducción se expone la normativa de control de esfuerzo pesquero analizada, se presentan datos sobre la estructura de la flota pesquera en España y su accidentalidad, y se detallan los criterios de estabilidad manejados durante el trabajo, explicando su relación con la seguridad de los pesqueros.

Seguidamente se realiza un análisis estadístico de la siniestralidad en el sector de la pesca para establecer si el conjunto de accidentes estudiados supone una anomalía, o si por el contrario el conjunto de estos accidentes no es relevante desde el punto de vista estadístico. Se analiza la siniestralidad a partir de diversas bases de datos de buques pesqueros en España y se concluye que el conjunto de accidentes estudiados supone una anomalía estadística, ya que la probabilidad de ocurrencia de los cinco sucesos es muy baja considerando la frecuencia estimada de pérdidas de buques por estabilidad en el subsector de la flota pesquera en el que se encuadran los cinco buques perdidos.

A continuación el trabajo se centra en la comparación de los buques accidentados con los buques pesqueros dados de baja para construir aquellos, según exige la normativa de control de esfuerzo pesquero; a estos últimos buques nos referiremos como “predecesores” de los buques accidentados.

Se comparan las dimensiones principales de cada buque y de su predecesor, resultando que los buques accidentados comparten características de diseño comunes que son sensiblemente diferentes en los buques predecesores, y enlazando dichas características de diseño con los requisitos de la nueva normativa de control del

esfuerzo pesquero bajo la que se construyeron estos barcos. Ello permite establecer una relación entre los accidentes y el mencionado cambio normativo.

A continuación se compara el margen con que se cumplían los criterios reglamentarios de estabilidad entre los buques accidentados y los predecesores, encontrándose que en cuatro de los cinco casos los predecesores cumplían los criterios de estabilidad con mayor holgura que los buques accidentados.

Los resultados obtenidos en este punto permiten establecer una relación entre el cambio de normativa de esfuerzo pesquero y la estabilidad de los buques.

Los cinco buques accidentados cumplían con los criterios reglamentarios de estabilidad en vigor, lo que cuestiona la relación entre esos criterios y la seguridad. Por ello se extiende la comparativa entre pesqueros a dos nuevos campos relacionados con la estabilidad y la seguridad delos buques:

- Movimientos a bordo (operatividad del buque), y
- Criterios de estabilidad en condiciones meteorológicas adversas

El estudio de la operatividad muestra que los buques accidentados tenían, en general, una mayor operatividad que sus predecesores, contrariamente a lo que sucedía con el cumplimiento de los criterios reglamentarios de estabilidad.

Por último, se comprueba el desempeño de los diez buques en dos criterios específicos de estabilidad en caso de mal tiempo: el criterio IMO de viento y balance intenso, y un criterio de estabilidad de nueva generación, incluyendo la contribución original del autor de considerar agua en cubierta. Las tendencias observadas en estas dos comparativas son opuestas, lo que permite cuestionar la validez del último criterio sin un control exhaustivo de los parámetros de su formulación, poniendo de manifiesto la necesidad de más investigaciones sobre ese criterio antes de su adopción para uso regulatorio.

El conjunto de estos resultados permite obtener una serie de conclusiones en la comparativa entre ambos conjuntos de buques pesqueros.

Si bien los resultados de este trabajo no muestran que la aprobación de la nueva normativa de esfuerzo pesquero haya significado una merma general de seguridad en sectores enteros de la flota pesquera, sí se concluye que permitió que algunos diseños de buques pesqueros, posiblemente en busca de la mayor eficiencia compatible con dicha normativa, quedaran con una estabilidad precaria, poniendo de manifiesto que la relación entre seguridad y criterios de estabilidad no es unívoca, y la necesidad de que éstos evolucionen y se adapten a los nuevos diseños de buques pesqueros para continuar garantizando su seguridad.

También se concluye que la estabilidad es un aspecto transversal del diseño de los buques, por lo que cualquier reforma normativa que afecte al diseño de los pesqueros o su forma de operar debería estar sujeta a evaluación por parte de las autoridades responsables de la seguridad marítima con carácter previo a su aprobación.

ABSTACT

Between 2004 and 2007 five small Spanish fishing vessels sank in stability related accidents. These vessels had similar characteristics, had relatively short age, and had been built in a period of a few years. Most crewmembers of these five vessels died or disappeared in those accidents.

This set of accidents had significant social and media impact. Among naval architects and seamen of the fishing sector these accidents were related to the design constraints imposed by the fishing control effort regulations. The accidents were investigated and the official reports issued; this alleged relationship was not explored.

This thesis aims to investigate the relationship between those accidents and changes in fishing effort control regulations.

In the introduction, the fishing effort control regulation is exposed, data of the Spanish fishing fleet structure and its accident rates are presented, and stability criteria dealt with in this work are explained, detailing its relationship with fishing vessel safety.

A statistical analysis of the accident rates in the fishing sector in Spain is performed afterwards. The objective is determining whether the set of accidents studied constitute an anomaly or, on the contrary, they are not statistically relevant. Fishing vessels accident rates is analyzed from several fishing vessel databases in Spain. It is concluded that the set of studied accidents is statistically relevant, as the probability of occurrence of the five happenings is extremely low, considering the loss rates in the subsector of the Spanish fishing fleet where the studied vessels are fitted within.

From this point the thesis focuses in comparing the vessels lost and the vessels that were decommissioned to build them as required by the fishing effort control regulation; these vessels will be referred to as “predecessors” of the sunk vessels.

The main dimensions between each lost vessel and her predecessor are compared, leading to the conclusion that the lost vessels share design characteristics which are sensibly different from the predecessors, and linking these design characteristics with the requirements imposed by the new fishing control effort regulations. This allows establishing a relationship between the accidents and this regulation change.

Then the margin in fulfilling the regulatory stability criteria among the vessels is compared, resulting, in four of the five cases, that predecessors meet the stability criteria with greater clearance than the sunk vessels.

The results obtained at this point would establish a relationship between the change of fishing effort control regulation and the stability of vessels.

The five lost vessels complied with the stability criteria in force, so the relation between these criteria and safety is put in question. Consequently, the comparison among vessels is extended to other fields related to safety and stability:

- Motions onboard (operability), and
- Specific stability criteria in rough weather

The operability study shows that the lost vessels had in general greater operability than their predecessors, just the opposite as when comparing stability criteria.

Finally, performance under specific rough weather stability criteria is checked. The criteria studied are the IMO Weather Criterion, and one of the 2nd generation stability criteria under development by IMO considering in this last case the presence of water on deck, which is an original contribution by the author. The observed trends in these two cases are opposite, allowing to put into question the last criterion validity without an exhaustive control of its formulation parameters; indicating that further research might be necessary before using it for regulatory purposes.

The analysis of this set of results leads to some conclusions when comparing both groups of fishing vessels.

While the results obtained are not conclusive in the sense that the entry into force of a new fishing effort control in 1998 caused a generalized safety reduction in whole sectors of the Spanish fishing fleet, it can be concluded that it opened the door for some vessel designs resulting with precarious stability. This evidences that the relation between safety and stability criteria is not univocal, so stability criteria needs to evolve for adapting to new fishing vessels designs so their safety is still guaranteed.

It is also concluded that stability is a transversal aspect to ship design and operability, implying that any legislative reform affecting ship design or operating modes should be subjected to assessing by the authorities responsible for marine safety before being adopted.

1. INTRODUCTION

1.1. General

Between November 2004 and September 2007, five Spanish-flagged fishing vessels capsized due to loss of stability resulting in a large part of their crew dead. Examining the five accidents side by side, it is noticeable that the vessels had similar characteristics, in particular that they had all been built between 1999 and 2001 and their lengths ranged between 15 and 24 meters. When they capsized, their age ranged from three to eight years.

The vessels had been designed and built according to the Spanish stability regulation in force established by the Order of the Ministry for Commerce on Stability Rules for Fishing Vessels dated on 29 July 1970 and published in the Official Journal of Spain in 19 August 1970 (*Orden del Ministerio de Comercio, de 29 de julio de 1970, sobre normas de estabilidad de buques pesqueros; BOE 198, 19 de agosto de 1970*). This regulation included the International Maritime Organization (IMO) stability criteria for fishing vessels, basically unmodified since 1970. According to this regulation, the righting lever curves (GZ curves) of fishing vessels had to comply with the following criteria:

1. The area under the GZ curve shall not be less than 0.055 metre-radians up to a heeling angel of 30º and not less than 0.09 metre-radians up to 40º or the angle of downflooding if this angle is less than 40º. Additionally, the area under the GZ curve between the angles of heel of 30º and 40º or the angle of downflooding if this angle is less than 40º, shall not be less than 0.03 metre-radians.

2. The righting lever GZ shall be at least 0.2 m at an angle of heel equal to or greater than 30º.

3. The maximum righting lever shall occur at an angle of heel not less than 25º, and preferably greater than 30º.

4. The initial metacentric height GM_o, corrected by the effect of free surfaces, shall not be less than 0.35 m.

However, the construction projects for these vessels had been elaborated not only adjusting to this framework but also complying with the Royal Decree (RD) 2287/1998. This regulation aimed at fulfilling some requirements imposed by the European Common Fisheries Policies (CFP), as well as at promoting the modernization of the

Spanish fishing fleet. This legislation substantially changed the existing regime in Spain regarding the fishing vessels tonnage limitation and, hence introduced new factors in their design that did not previously exist. One wonders whether that legislation could have affected the design so much as to impair the safety of these vessels, as suggested by some authors (Gefaell-Chamochín, 2005a, 2005b).

1.2. Fishing effort

1.2.1. General

One of the main problems facing the global fishing industry is that there are too many boats chasing too few fish. In 1992, the Food and Agriculture Organization (FAO) estimated that the total fishing capacity of the world fleet was approximately twice what was needed to harvest the oceans at the highest sustainable rate. Analogous studies at EU level have concluded that many European fleets are exerting a fishing pressure on the ocean which is two to three times the predicted sustainable level. In this context, one of the priorities of the CFP, established initially in 1983, has been to bring the European fleet in tune with the available resources of the sea (European Commission, 2009); fishing effort control has been one of its main instruments.

The fishing effort for a vessel is defined as the product of its capacity and activity. For a group of vessels, the fishing effort is defined as the sum of the individual fishing efforts. A wide variety of methods for measuring the fishing effort have been developed over time, ranging from just keeping track of the number of vessels to sophisticated fish finders and satellite monitoring of vessel activity (Anticamara et al., 2011).

The fishing capacity is defined as the ability of a vessel or group of vessels to catch fish. There are two approaches to the quantification of capacity.

- The economic approach, which defines the capacity of a vessel or group of vessels as the maximum output, or maximum amount of fish than can potentially be caught over a certain period of time, provided that the vessels are fully utilized and the stocks remain healthy.

- The other approach, generally adopted by fishery management bodies, bases the quantification of the fishing capacity on the 'potential' for fleets to constitute an input to the fishery in terms of generation of fishing mortality. This quantification of the maximum potential input may be based on the vessel and fishing gear characteristics, which may also be referred to as fishing capacity parameters.

In the framework of the Common Fisheries Policy, fishing capacity has so far been quantified on the basis of vessel characteristics. This approach dates back to the first multiannual guidance programs adopted in the early 1980's. The fishing capacity indicators chosen at the time were vessel tonnage and engine power, these have been included in the basic regulation of the CFP which also allows for the possibility to define the fishing capacity in terms of the amount and/or size of the fishing gear (European Commission, 2007).

Consequently, the approved multiannual guidance programmes for the fishing fleets of the European countries established limits in the total tonnage (in GT) and engine power (in kW) of segments of the fishing fleets. For instance, according to the multiannual guidance programme for the fishing fleet of Spain for the period from 1 January 1997 and 21 December 2001, the objectives for the whole fleet were 799253 GT and 1755636 kW (Commission Decision 98/128/EC of 16 December 1997, published in the Official Journal of the European Commission on 12 February 1998).

1.2.2. Fishing effort regulation in Spain: Royal Decree 2287/1998

The control of fishing effort is a vital part of fisheries management. In the framework of the European Common Fisheries Policies, a tool to exert such control has been the limitation of tonnage (measured as gross tonnage GT) and propulsion power. Major milestones in these policies have been the promulgations of the Multi-Annual Guidance Programmes in the period 1983-2007 (Perez-Labajos, 2012). In Spain, several regulations to control the fishing effort based on tonnage and power have been approved in order to fulfill the objectives of the CFP and the Multi-Annual Guidance Programmes. In the late nineties, RD 798/1995, modified by RD 1040/1997 and RD 2287/1998, established a regulatory framework to develop CFP in Spain.

This standard established the conditions of approval for the construction of new fishing vessels. Roughly speaking, any new construction authorization required the decommissioning of an existing vessel, representing at least 100% of the gross registered tonnage (GRT) and the propulsive power of the new construction.

The 1995 rule was modified in 1997 in order to incorporate the gross tonnage (GT) substituting GRT as the tonnage measure.

In November 1998 the RD 2287/1998 was promulgated. Such a rule was aimed at regulating the spaces on board fishing vessels with a two-fold objective. First, improve the safety of working conditions, the quality of the products and the accommodation of the crews. Second, to fulfill the objectives of the Multiannual Guidance Program for the fishing fleet of Spain (1997-2001) (European Commission, 1998).

Following the amendment, two different regimes to calculate the tonnage of new vessels, depending on the length of the ship, were established:

A. Ships with a length smaller than 15 meters: the GT of the new ship could be increased by a factor of 1.1 on the total GT of the decommissioned ship.

B. Ships with a length larger than or equal to 15 meters: the GT of new ships could be increased on the total GT of the decommissioned ship by a factor according to Table 1:

Territorial and European waters	
Regime A	Factor
Trawlers Fixed fishing gears Seiners	1.7 1.6 1.35
International and third country waters	
Regime B	Factor
Trawlers and moving fishing gears Fixed fishing gears Tuna vessels	1.7 1.6 1.4

Table 1. GT increase factors from RD 2287/1998

For ships with an overall length larger than or equal to 15 meters, the volume below the main deck of the new vessel could be increased by 10% with respect to that of the de-registrations. Therefore, the increase contemplated in Table 1 should be achieved in practicality by closed spaces above the main deck.

RD 2287/1998 was mandatory until October 2009 when it was derogated by the RD 1549/2009, which again requested de-registrations with a gross tonnage (GT) and a propulsion power at least as large as those of the new vessels.

1.3. Influence of the tonnage limitation on stability

The tonnage increase in boats with a length greater than 15 meters allowed by the 1998 norm was in practice mostly destined to increase closed spaces above the tonnage deck, thereby improving working conditions and safety of workers on board fishing vessels. However, such an increase implied larger superstructures, with the subsequent increase of heavy weights, leading to certain equipment, including parts of heavy fishing gear or cargo, being stowed in high positions. This implied a rise of the ship's center of gravity, an increase of the wind exposed area and, possibly, a deterioration of the stability of ships built under the new rules.

The weight increase due to larger superstructures generally implies an increase in draft and a subsequent reduction of the freeboard. Such a freeboard reduction cannot be unwound by the designer through an increase of the volume below tonnage deck since it is limited by the 1998 RD. This invariably reduces the vessel's stability margin with respect to the IMO regulatory stability criteria: on one side, the buoyancy reserve relative to the displacement of the ship is reduced and on the other hand the angle of immersion of the tonnage deck is also reduced.

1.4. Characteristics of the fishing sector in Spain

1.4.1. Importance of the Spanish fishing sector at global level

Spain has the most important fishing sector of the EU (European Commission, 2012). On 1st September 2009 the total tonnage of the Spanish fishing fleet reached 447000 GT, concentrating 24% of the global EU fleet tonnage. The United Kingdom (UK) was the second country per fishing fleet tonnage, with 200000 GT, less than one half of the Spanish fleet. At the same dates Spain had more than 11000 fishing vessels registered, while UK had 6500 vessels. These figures are below Italy (13600 vessels) and quite below Greece, with 17000 units. These data indicate that those fleets are composed mainly of small units.

Employment is another indicator of the importance of the fishing sector. According to EU data in 2007 the fishing sector in Spain employed 35274 workers (measured in full time equivalent working days), while the whole European Union employed 141110 workers. Therefore, Spain employed one third of the fishing sector workforce in Europe. UK employed 8000 workers.

Per volume of catches, Spain is again on top of the European countries with catches of 736000 ton in 2007, 14% of the total catches of the EU. For comparative purposes, UK was close in the list, with catches of 616000 ton (12% of the total catches of the EU). Nevertheless, at this respect Spain is not a relevant country at international level, and is not among the 17 main producers for volume of catches. China is in the first position of this list with 14.6 Mt (million tons) that accounts for 16% of the world production, followed by Perú (7 Mt, 8%) and the EU (5 Mt, the 5.7% of the world catches).

1.4.2. Distribution of the Spanish fishing fleet

The Spanish Ministry for Agriculture, Food and Environment (MAGRAMA) keeps the Spanish Fishing Fleet Register (SFFR) of Spanish fishing vessels in which relevant data, such as length, tonnage, power, year of registration, cause of the de-registration, de-registration year, fishery, etc. are stored. This census is accessible online on the

ministry's web page (http://www.magrama.gob.es/es/pesca/temas/la-pesca-en-espana/censo-de-la-flota-pesquera/censo.asp).

The European Union maintains a general fishing vessel database for all EU countries, accessible through the internet link

http://ec.europa.eu/fisheries/fleet/index.cfm?lg=en.

Using the data collected from these sources it is possible to carry out a statistical analysis of the Spanish fishing fleet.

A total of 26780 fishing vessels have been commissioned in Spain since 1870. Their distribution according to length and fishing gear is presented in Table 2 and Figure 1.

Overall length L (m)	L > 24	24>=L> 15	15 >=L> 6	L <= 6	Total
Dredges	0 (0.0% / 0.0%)	0 (0.0% / 0.0%)	87 (30.2% / 0.8%)	201 (69.8% / 2.1%)	288 (100% / 1.1%)
Gilnets and entangling nets	48 (0.3% / 1.8%)	351 (2.2% / 10.0%)	7446 (47.0% / 68.3%)	7987 (50.4% / 82.0%)	15832 (100% / 59.1%)
Hook and lines	466 (11.7% / 17.6%)	378 (9.5% / 10.8%)	1775 (44.5% / 16.3%)	1371 (34.4% / 14.1%)	3990 (100% / 14.9%)
Seines	375 (18.2% / 14.2%)	874 (42.5% / 24.9%)	784 (38.1% / 7.2%)	25 (1.2% / 0.3%)	2058 (100% / 7.7%)
Traps	1 (0.4% / 0.0%)	8 (3.4% / 0.2%)	113 (47.7% / 1.0%)	115 (48.5% / 1.2%)	237 (100% / 0.9%)
Trawls	1751 (40.0% / 66.3%)	1894 (43.3% / 54.0%)	692 (15.8% / 6.4%)	38 (0.9% / 0.4%)	4375 (100% / 16.3%)
Total	2641 (9.9% / 100%)	3505 (13.1% / 100%)	10897 (40.7% / 100%)	9737 (36.4% / 100%)	26780 (100% / 100%)

Table 2. Distribution of the fishing fleet commissioned in Spain since 1870, per length and fishing gear (Source: SFFR)

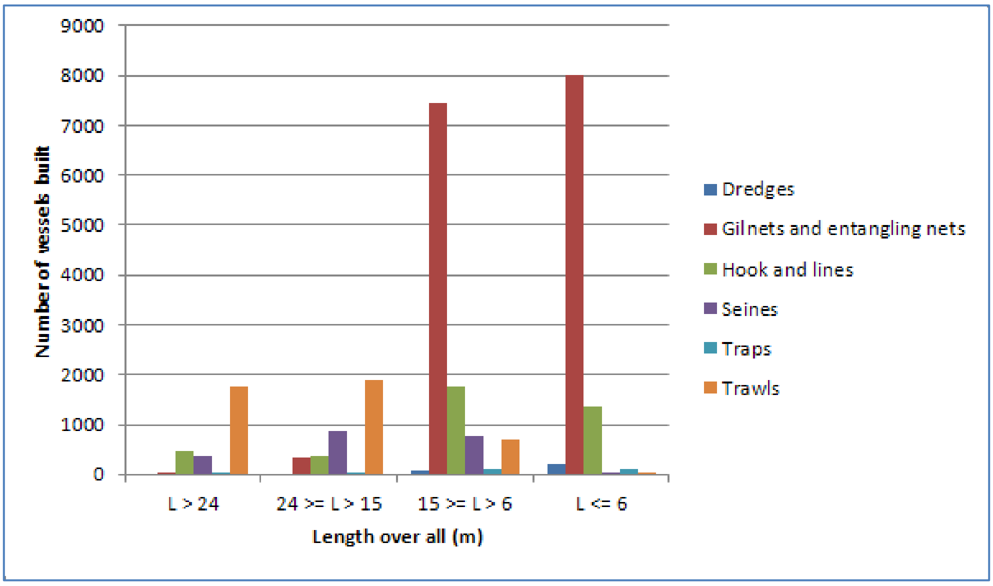


Figure 1. Historical Spanish fishing fleet distribution, by length and fishing gear type (Source: SFFR)

Considering the fleet in service, the total number of fishing ships amounts to 9986 (as of May 2013), with the length and fishing gear type distribution shown in Table 3. It can be seen that in both cases, the bulk of the fleet corresponds to small fishing vessels (less than 15 meters in length).

Overall length L (m)	L > 24	24>=L> 15	15 >=L> 6	L <= 6	Total
Gilnets and entangling nets	13 (0.2% / 1.5%)	119 (1.7% / 10.2%)	3693 (53.0% / 79.1%)	3138 (45.1% / 94.7%)	6963 (100% / 69.7%)
Hook and lines	232 (18.3% / 27.5%)	131 (10.3% / 11.3%)	726 (57.3% / 15.6%)	177 (14.0% / 5.3%)	1266 (100% / 12.7%)
Seines	171 (26.0% / 20.3%)	329 (50.0% / 28.3%)	158 (24.0% / 3.4%)	0 (0.0% / 0.0%)	658 (100% / 6.6%)
Trawls	427 (38.9% / 50.7%)	582 (53.0% / 50.1%)	90 (8.2% / 1.9%)	0 (0.0% / 0.0%)	1099 (100% / 11.0%)
Total	843 (8.4% / 100%)	1161 (11.6% / 100%)	4667 (46.7% / 1000%)	3315 (33.2% / 100%)	9986 (100% / 100%)

Table 3. Distribution of the current fishing fleet, as of May 2013, per length and fishing gear (Source: SFFR)

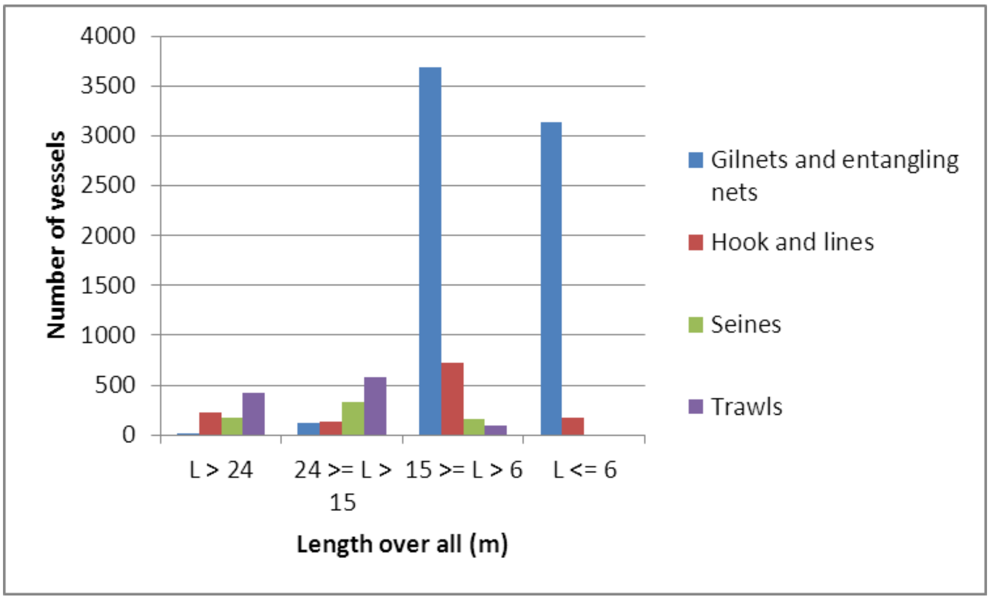


Figure 2. Distribution of the current fishing fleet, as of May 2013, per length and fishing gear (Source: SFFR)

For a better understanding of the types of fishing vessels and gears referred to in the tables above, the multilingual dictionaries of fishing vessels and fishing gear (*Multilingual dictionary of fishing gear*, 1992, *Multilingual dictionary of fishing vessels and safety on board*, 1992) may be consulted. These are available online at:

http://ec.europa.eu/fisheries/documentation/publications/index_en.htm

1.4.3. Division of the fleet according to the operation model

A widely accepted classification of fishing vessels divides the fleet in two sectors according to the operation model: Coastal / artisanal fleet vs. industrial fleet, though sometimes the distinction is not absolutely clear due to the existence of vessels which cannot undoubtedly be classified in one category or another.

Coastal-artisanal fleet: It is composed of vessels that fish close to their base port. Coastal vessels rarely stand at sea more than one week, while artisanal vessels normally go fishing and return to port daily. Vessels are of small size, up to 20 GRT and length 15 m for the artisanal vessels, and up to 100 GRT and 24 m for coastal vessels.

Vessels have a low degree of mechanization and the manual force is the predominant production factor, therefore the power / crewmember ratio or the power / GRT ratio are lower than in the industrial fleet. The degree of specialization among crewmembers is low. Productivity is highly dependent of the human force and the skills of fishermen.

The shipowner is one person or family and the number of crewmembers rarely exceeds 10, being frequent that some of them work simultaneously at shore. It is also common the shipowners being also part of the crew, and some crewmembers being the shipowner relatives. Usually the shipowner is also the master of the vessel. Retribution is paid after selling the catches of the day, and salaries are proportional to the daily amount obtained.

Industrial fleet: Vessels that fish far from their base ports, standing at sea between 10 and 30 days (sea vessels), and about two months in the case of high sea vessels. 99% of the vessels are longer than 24 m, having the largest vessels (big tuna vessels) lengths close to 100 m. Their size is over 100 GRT, more than 250 GRT for high sea vessels.

Both the capital invested per crewmember and the mechanization degree are higher than in the coastal-artisanal fleet. Therefore therefore the power / crewmember ratio or the power / GRT ratio are higher.

In general vessels are corporate properties and the number of crew is high, more than 12 and up to 50-60 members in the largest vessels. The higher degree of organization and specialization in work confers to these boats characteristics of an industrial centre.

The payment system tends to be on a job to job basis, either proportionally to the earnings, either as a fixed low salary and a high fishing bonus. This irregular earnings, as well as the extended working hours (determined by fishing), are all factors that may not be unrelated to the rate of work accidents occurring in the industrial fleet.

The fleet distribution per fishing type and gear is shown in Table 5.

Fishing / gear type	Artisanal – coastal fleet		Industrial fleet		Total
	Artisanal (< 20 GRT)	Coastal fishing (<100 GRT)	Sea fishing (<250 GRT)	High seas fishing (>250 GRT)	
Gilnets and entangling nets	6875 (98.7% / 83.6%)	85 (1.2% / 7.1%)	2 (0.0% / 0.5%)	1 (0.0% / 0.7%)	6963 (100% / 69.7%)
Drifting longlines	46 (19.0% / 0.6%)	84 (34.7% / 7.0%)	80 (33.1% / 19.1%)	32 (13.2% / 22.9%)	242 (100% / 2.4%)
Set longlines	882 (86.1% / 10.7%)	79 (7.7% / 6.6%)	63 (6.2% / 15.1%)	0 (0.0% / 0.0%)	1024 (100% / 10.3%)
Bottom otter trawls	213 (19.5% / 2.6%)	612 (56.1% / 51.0%)	201 (18.4% / 48.1%)	65 (6.0% / 46.4%)	1091 (100% / 10.9%)
Purse seines	212 (32.2% / 2.6%)	340 (51.7% / 28.3%)	72 (10.9% / 17.2%)	34 (5.2% / 24.3%)	658 (100% / 6.6%)
Bottom pair trawls	0 (0.0% / 0.0%)	0 (0.0% / 0.0%)	0 (0.0% / 0.0%)	8 (100.0% / 5.7%)	8 (100% / 0.1%)
Total	8228 (82.4% / 100%)	1200 (12.0% / 100%)	418 (4.2% / 100%)	140 (1.4% / 100%)	9986 (100% / 100%)

Table 4. Spanish fishing fleet distribution, as of May 2013, per fishing type and fishing gear (Source: author from EU data)

The vast majority of the Spanish fleet is composed of artisanal vessels, most of the gillnets / entangling nets type. Half of the vessels of the industrial fleet, which accounts for less than 6% of the vessels, are trawlers.

1.5. Mortality of the fishing sector

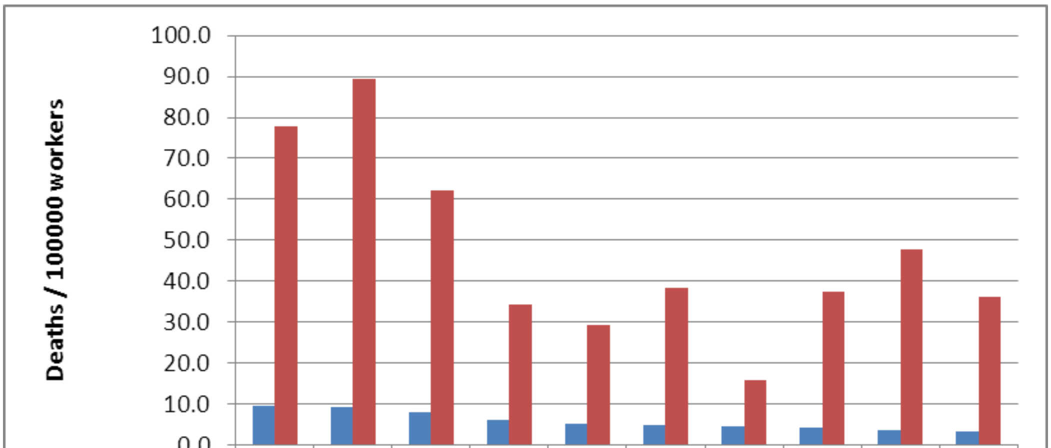
According to data published by relevant national and international organizations, fishing is among the labor sectors with the highest mortality rates.

1.5.1. National dimension

In Spain, figures published by INE (National Statistics Institute, *Instituto Nacional de Estadística*, http://www.ine.es/inebmenu/indice.htm), shows the global rate of mortal accidents in 2011 to be 3 deaths for each 100000 workers in Spain (global rate: for all labour sectors). The global rate of severe accidents in Spain in the same year was 25 by every 100000 workers. In the fishing sector only, the rate of mortal accidents in that year was of 33 deaths, that is to say, more than ten times the global rate. Similarly, the ratio of severe accidents in the fishing sector rose to 159 per 100000 workers (six times the global rate).

According to these data, the fishing and aquiculture labor sector was the third with highest mortality rates in Spain, only behind silviculture[1] (51 deaths x 100000 workers) and extractive industries[2] (42 deaths x 100000 workers).

The International Labour Organization (ILO) has published data of mortality in Spain between 1999 and 2008, available through their website http://laborsta.ilo.org/. In that period the fishing sector mortality rate varied between 15 and 90 deaths x 100000 workers, with a clear tendency to its reduction. Considering the global mortality rate, figures also show a decreasing tendency in those years (see Figure 3).



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
All sectors	9.5	9.2	8.0	6.1	5.3	4.9	4.5	4.4	3.6	3.3
Fishing sector	77.9	89.3	62.3	34.3	29.4	38.4	15.9	37.4	47.8	36.1

Figure 3. Mortality rates in Spain (Source: ILO)

The ratio of mortality in fishing sector to global mortality in all labor sectors goes from 3.5 to 13.3 (Figure 4) with a mean value of 8.1. These figures from ILO are coherent with the national statistics published by INE.

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[1] Silviculture: practice of controlling the establishment, growth, composition, health, and quality of forests to meet diverse needs and values

[2] Extractive industries: mines and quarries exploitation

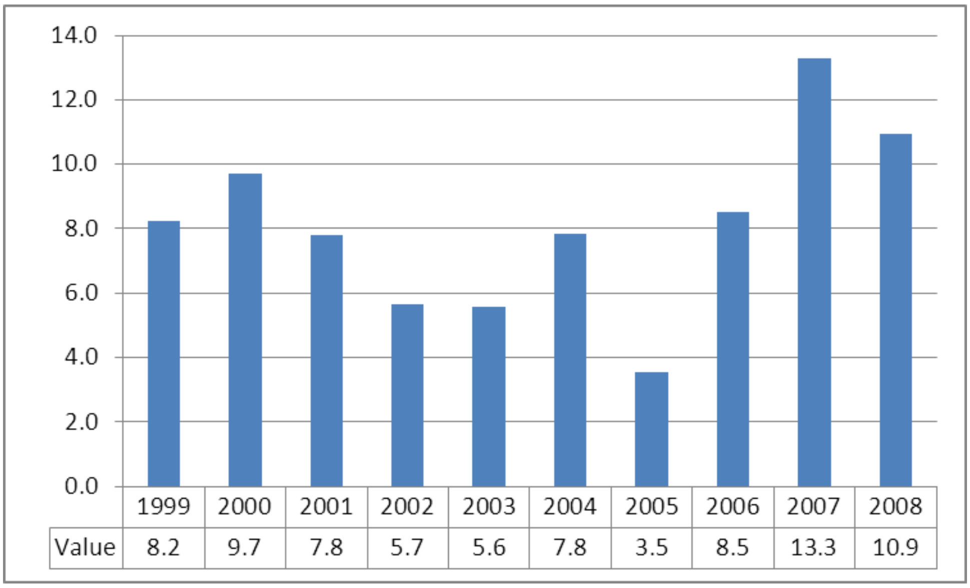


Figure 4. Ratio of mortality rate in fishing sector to global mortality in all labor sectors in Spain, from 1999 to 2008 (Source: Author from ILO data)

Historic data of maritime accidents are not easily available for several reasons. Firstly, the publication of maritime accident investigations reports was not compulsory in Spain until Royal Decree 862/2008 entered into force in September 2008. Although the General Directorate for the Merchant Marine (*Dirección General de la Marina Mercante*, DGMM) had been systematically investigating maritime accidents for several years, it was not until 2010 that part of those reports were published. Even today DGMM has published only a reduced number of reports and has not elaborated public statistics of maritime accidents.

This situation changed with the creation in 2008 of the Maritime Accident and Incident Investigations Standing Commission (*Comisión Permanente de Investigación de Accidentes e Incidentes Marítimos*, CIAIM), pursuant to Directive 2009/18/EC. CIAIM is a collegial body with the task to investigate maritime accidents in Spain. CIAIM has published all the reports of the accidents investigated, as required by Directive 2009/18/EC. CIAIM has also elaborated annual reports with statistical data of the maritime accidents happened and investigated every year (CIAIM, 2012, 2011, 2010, 2009).

According to CIAIM data, 422 maritime accidents or incidents occurred in Spain between October 2008 and April of 2013, which implies a mean value of 7.5 per month. In 191 of those occurrences (45%) fishing vessels were implied. The total number of vessels lost in that period rises to 131, 81 of which are fishing vessels. This number of lost fishing vessels equals approximately 1% of the Spanish fishing fleet.

That is to say, around one fishing vessel of every hundred is lost for accidental causes every four years.

1.5.2. International dimension

In other developed countries the mortality in the fishing sector reaches similar levels. In the United States (US) there are around 130 fatalities per year for every 100000 fishing sector workers, compared to 4 for the rest of sectors (Lincoln and Lucas, 2010); similar alarming figures are reported in the UK (UK MAIB, 2010). Nonetheless, the global available data is scarce (Perez-Labajos, 2008), and published analyses are therefore usually supported by local or national fleet data (Jaremin, 2004; Loughran et al., 2002; Wang et al., 2005) with some using methodologies which can be applied globally (Perez-Labajos et al., 2006).

At international level it can be stated that few countries notify the International Maritime Organization (IMO) data on maritime accidents, especially regarding fishing vessels. According to IMO (IMO, 2012), between 2001 and 2010 only three of 165 IMO members on average communicated data on fishing vessels and fishermen accidents (Table 5).

Year	Number of countries notifying fishing accidents to OMI	Number of IMO members
2000	7	160
2005	3	166
2010	3	169

Table 5. Countries notifying fishing accidents to IMO (source: IMO)

At European level consolidated data on maritime accidents do not exist either. EMSA (*European Maritime Safety Agency*) publishes annual reports with statistics of maritime accidents notified by EU member states, pursuant to Directive 2009/18/EC, which entered into force on June 2011. Notwithstanding that obligation, many EU member states still do not notify maritime accidents. According to CIAIM estimations, on June 2013 only nine member states notified regularly maritime accidents to EMSA. In addition, regarding fishing vessels the Directive covers only fishing vessels with length greater than 15 m. For all these reasons no homogeneous and reliable data about fishing vessels accidents are available at European level or international level.

However, FAO (Food and Agriculture Organization) estimated that in 2001 the global workforce in the fishing sector was 15 million, accounting neither aquiculture nor part-time workers. This organization estimated in 24000 the numbers of yearly

accidental deaths in the fishing sector (FAO, 2001). This implies that the mortality rate in the fishing sector that year at global level was 160 deaths per 100000 workers.

1.6. Stability and safety

1.6.1. General

Small commercial fishing vessels are the largest, most diverse, and constantly evolving class of marine vessels in existence. Yet the methods used to evaluate their stability reflect a one size fits all approach with little improvement over the many decades since their introduction in the early 1900s. This conflict coupled with significant flaws in the methods used to convey stability guidance to the crews leads to unacceptable risks being taken and fishing vessels and their crews being lost. Improvements are needed in all areas of small commercial fishing vessel analysis: better criteria that reflect the true dynamic environment faced by the crews, better means to convey stability guidance, including the current risk of capsize to the crews, and lastly a program to teach stability and how to use the guidance provided (Womack, 2003).

The current intact stability framework for fishing vessels in Spain is based on the IMO intact stability rules. This framework was published in the Royal Decree 543/2007 (*Real Decreto 543/2007 de 27 de abril, por el que se determinan las normas de seguridad y de prevención de la contaminación a cumplir por los buques pesqueros menore sde 24 metros de eslora L, BOE 131, 1 junio 2007*), and comprises the following criteria for vessels with length over 12 m and below 24 m, which are well known to all naval architects:

5. The area under the righting lever curve (GZ curve) shall not be less than 0.055 metre-radians up to a heeling angel of 30º and not less than 0.09 metre-radians up to 40º or the angle of downflooding if this angle is less than 40º. Additionally, the area under the GZ curve between the angles of heel of 30º and 40º or the angle of downflooding if this angle is less than 40º, shall not be less than 0.03 metre-radians.

6. The righting lever GZ shall be at least 0.2 m at an angle of heel equal to or greater than 30º.

7. The maximum righting lever shall occur at an angle of heel not less than 25º, and preferably greater than 30º.

8. The initial metacentric height GM_o, corrected by the effect of free surfaces, shall not be less than 0.35 m.

In addition to these criteria, when the dynamic stability at 30º (area under GZ curve up to 30º) is lower than 0.065 metre-radians, the vessel is required by the rules to withstand:

9. the effect of severe wind and rolling[3], and

10. the effect of water on deck[4].

This regulation replaced in 2007 the previous stability criteria established in 1970 by Order of the Ministry for Commerce on Stability Rules for Fishing Vessels dated on 29 July 1970 and published in the Official Journal of Spain in 19 August 1970. The set of stability criteria in force before 2007 comprised the same criteria applicable to the GZ curve (criteria 1 to 5 of the previous list) but did not include provisions to withstand the effect of water on deck nor the effect of severe wind and rolling.

Being the ship stability in intact condition such a fundamental quality, it is expectable that appropriate regulations have been developed to deal with this matter, and to help designers in designing safer ships. Presently, intact stability rules for passenger, cargo or fishing vessels not covered by specific IMO instruments, are based on the "International Code on Intact Stability, 2008 (2008 IS Code)". Reference to the 2008 IS Code is presently made by SOLAS and by the International Convention on Load Lines.

Together with 2008 IS Code, explanatory notes have been issued (see MSC.1/Circ.1281) reporting some of the historical and theoretical background of the 2008 IS Code, together with some additional topics (e.g. alternative to the "25 deg" requirement for the maximum of GZ curve).

1.6.2. Origin and limitations to stability criteria

Current stability regulations are mainly based on righting lever curve properties. The idea of systematically judging ship safety in intact condition through parameters of the GZ curve can be dated back mostly to the works of of Jaakko Rahola (Rahola, 1939). Rahola analysed a series of 34 capsizing cases which occurred in the period 1870 (battleship "Captain") to 1938 (motor ship "Monica"). These accidents were analysed and commented in view of the characteristics of the righting curves of the capsized vessels. On the basis of the analysis carried out, Rahola proposed a series of requirements which are not significantly different from what we apply now. It is quite interesting to read what Rahola wrote at the end of the introduction to his PhD thesis (p.7): "*Quite aware of this, the author cannot by any means hope that the methods set forth in this study, or even any of the simplifying modifications of them, can be taken as*

[3] This criterion is based on the IMO Weather Criterion

[4] This criterion is based on the provisions of the Torremolinos Convention 77/93 on Safety of Fishing Vessels, Chapter III §6

the basis for some stability statute. When once the establishing of a statute for a standard stability has in the end become absolutely unavoidable, the theory of ships has perhaps advanced so far that the use of altogether new calculating methods for the minimum stability has become possible. The collecting of as extensive material as possible concerning accidents will nevertheless even then be essential, and in that respect the present investigation may be of lasting value".

Despite this and other warnings by subsequent authors, the international community considered the Rahola's approach as a reasonable tool for improving the safety level of ships. According to MSC.1/Circ.1281 (IMO, 2008), in 1966 and later in 1985, casualty records were collected by IMCO/IMO, eventually for a total of 93 passenger and cargo ships and for 73 fishing vessels. Following, basically, the same idea in the Rahola's approach (Rahola, 1939), parameters of the GZ curve of vessels involved in casualties were collected and tabulated, together with details of casualties.

A similar analysis was done on a sample of 62 passenger and cargo vessels and 48 fishing vessels which were operated safely. The intention was to compare vessels which were safely operated against those which suffered serious accidents, in order to determine reference limiting values for each parameter characterizing the GZ curve.

Two types of analyses were carried out:

- A qualitative analysis: this analysis "allowed qualitative conclusions with regard to the circumstances of casualties to be developed and therefore the specification of general safety precautions" (MSC.1/Circ.1281);
- A quantitative analysis: in this analysis "stability parameters of ships reported as casualties were compared with those for ships which were operated safely" (MSC.1/Circ.1281)

The main outcomes from the qualitative analysis can be summarized as follows (MSC.1/Circ.1281):

- The majority of casualties occurred in ships of less than 60 m in length;
- In 35 cases of the 80 cargo ships reported, deck cargo was present;
- The majority of casualties (72% of all casualties) occurred in restricted water areas, in estuaries and along the coastline. This is consistent with the reduced dimension, on average, of involved vessels;
- The most dangerous season was found to be autumn (41% of all casualties);
- About 75% of all casualties occurred in rough seas at a wind force of between Beaufort 4 to 10. Ships were sailing most often in beam seas, less often in quartering and following seas;

- The most common casualty was through gradual or sudden capsizing. In about 30% of casualties, ships survived the casualty and were heeled only;

The parameters used in the quantitative analysis, eventually were:

- GM0 : initial metacentric height
- GZ20, GZ30, GZ40 : GZ at 20deg, 30deg and 40deg respectively
- GZm : max GZ
- ϕ m : angle at which GZm occurs
- e40 : levers of dynamic stability (area under GZ curve) up to 40deg

Discrimination analysis and plots were prepared.

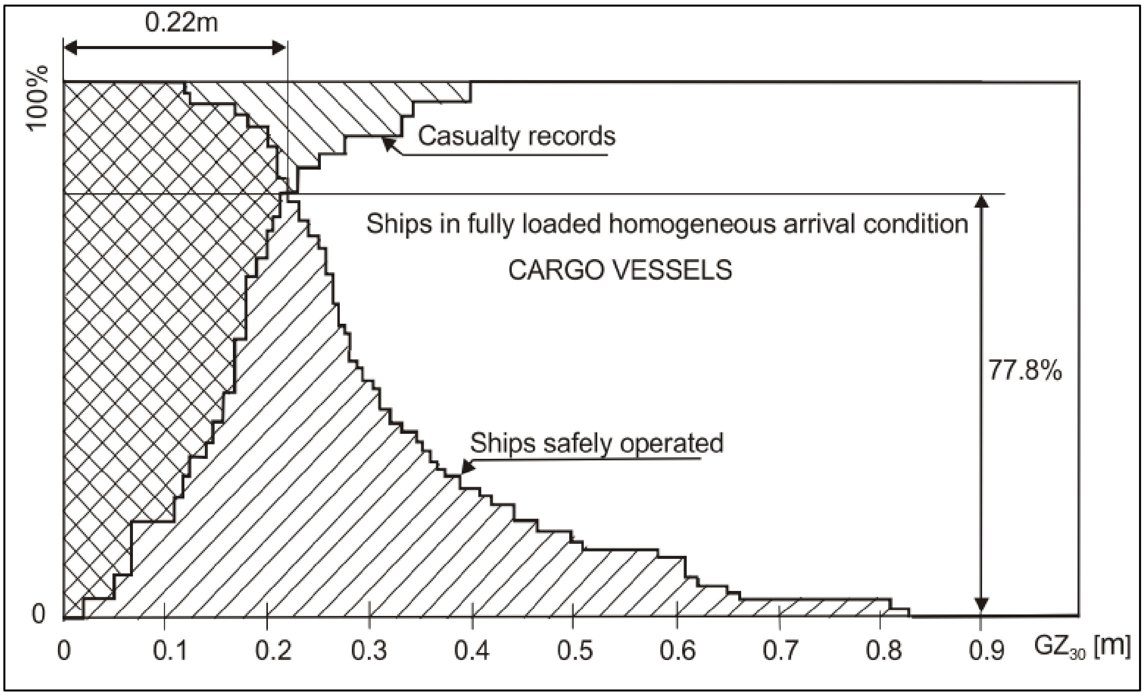


Figure 5. Discrimination analysis diagram for parameter GZ_{30} (MSC.1/Circ.1281)

According to the discrimination analysis diagram of Figure 5, the probability of capsizing of a ship with the considered parameter (GZ_{30} in this case) higher than the critical value is the same as the probability of survival of a ship with this parameter lower than the critical value. In order to increase the probability of survival, the value of the parameter should be increased, say up to 0.4 (Figure 5), at which the probability of survival (based on the population investigated) would be 100%. However, this would

mean excessive severity of the criterion, which usually is not possible to adopt in practice.

Diagrams were prepared jointly for cargo and passenger vessels and for fishing vessels, except vessels carrying timber deck cargo. Sets of diagrams were also separately prepared for cargo ships and fishing vessels. Diagrams in the form as shown in Figure 5 were prepared separately for each stability parameter and separately for cargo and passenger ships and for fishing vessels. After discussion, the stability criteria were rounded off and finally adopted in the form as they appear in the IMO resolutions A.167(ES.IV) and A.168(ES.IV).

At the end, stability criteria regarding the stability curves were agreed on the basis of discrimination analyses performed over a population of some dozens of vessels.

What is interesting is the fact that in the origin, the criteria acknowledges the existence of a percentage of vessels which could be unsafe even fulfilling the stability criteria. The origin of these criteria is a statistic study based on the survivability probabilities of a population of vessels, but it does not enter to examine directly the dynamic phenomena involved. Later additions to the criteria (the meteorological or water on deck criteria) still are mostly based on semi-empirical or partially semi-empirical approaches. From the practical point of view they are quite good “technical recipes” but they lack a solid framework and a solid theoretical background.

1.6.3. New approaches to the ship stability

The five lost vessels under study complied with the IMO stability regulations, implemented in the Spanish legislation in 1970. Despite this fact, the lack of stability caused all accidents. In some cases, dynamic phenomena not properly addressed by the regulatory stability framework were present.

Given the growing complexity and specialization of vessels, and also given the fact that the current stability criteria do not properly cover part of the dynamic phenomena present in several stability related accidents due to the limitations explained in the previous section, the IMO has recognized that the current stability framework can be improved, and the necessity to explore new approaches to develop new intact stability criteria which could capture the complexity of the dynamics experienced by seagoing vessels. It has therefore established working groups to develop the so called “Second Generation Intact Stability Criteria” (IMO, 2009). This new regulation is still under development and has not yet been approved by the IMO. Surely those works will constitute the basis of future stability regulations, which sooner or later will apply to fishing vessels.

IMO is fostering the development of a Second Generation Intact Stability Criteria (SGISC) to complement the current IMO intact stability regime. The IMO Sub-

Committee on Stability and Load Lines and Fishing Vessels at its 45th meeting in 2002 (SLF 45) established a working group with the long-term aim to redefine the Intact Stability Code according to a performance standards approach (SLF45/14-§6.4.1), (Francescutto, 2004)

By SLF 52 the working group had developed a framework which contained some important concepts (Bulian, 2012):

- A list of “failure modes” to be addressed by the stability criteria
- The introduction of the concept of “vulnerability criteria”
- The 3+1 tiers structure of the Second Generation Intact Stability Criteria, comprising, for each failure mode:
    - Two levels of “vulnerability criteria”
    - A “direct assessment level”
    - Operational guidance for those cases where only design countermeasures were not sufficient (the “+1” tier).

In its current status (November 2013), the SGISC framework contemplates the following failure modes:

- Pure loss of stability
- Parametric roll
- Surf-riding / broaching
- Dead-ship condition
- Excessive accelerations

Vulnerability criteria and associated methodologies to assess them are far from being firmly established, and the working group still has a long way ahead. The SLF Subcommittee instructed the working group (SLF 55-WP.1-§3.7) to review the plan of action for intact stability work (SLF 54/WP.3, annex 4) and prepare a revised plan, identifying priorities, time frames and objectives for the work to be accomplished. The current status is as follows (SLF 55/3/1):

- Draft vulnerability criteria for pure loss of stability and parametric rolling were agreed, but several items are undecided.
- Draft vulnerability criteria for broaching are at advanced stage of development, with two undecided items (standard of the Level 2 criterion and the range of maximum Froude number for calm-water resistance data to be used).

- Draft vulnerability criteria for dead-ship condition are at advanced stage of development. Two slightly different calculation methods of failure probability are provided and it is an item to be decided.
- Draft vulnerability criteria for excessive acceleration were proposed, but some elements such as roll damping prediction method to be used, are not specified.

In this work the author has examined the behavior of the ten vessels under study only in the dead ship condition, for the following reasons:

- It is the failure mode for which methodologies are more mature.
- Small fishing vessels are unlikely to suffer parametric roll or excessive acceleration, although some types of mid-size trawlers may be prone to suffering parametric roll (Míguez González, 2012).
- The dead ship condition is very relevant for small fishing vessels, especially for those that must remain adrift without power or maneuverability when pulling catches onboard.

In a future work, the study of the remaining failure modes for the ten vessels could be undertaken. Specifically broaching is considered of utmost importance for this kind of vessels.

While not contemplated specifically in the methodologies proposed to IMO for the dead ship condition, the author has studied this failure mode for the ten vessels considering water on deck. This is an original contribution by the author that is believed to be relevant for small fishing vessels, that operate normally with low freeboards and suffering numerous water shipments.

2. OBJECTIVES OF THE THESIS

2.1. Fishing effort control regulation influence on ship stability

The main objective of this work is to study the relationship between the accident rates in a sector of the Spanish fishing fleet and a change in the fishing effort control regulations occurred in Spain in 1998. That change is believed to have had negative influence over fishing vessels built from its entry into force, favoring the occurrence of some stability related accidents happened afterwards.

The fishing effort control regulation is one of the main design drivers in fishing vessels; that is, imposes drastic limitations to the designs. Consequently, a change in these regulations would affect a vessel's design, and therefore her stability.

2.2. Regulatory stability criteria aptitude to assess the probability of capsizing

In parallel, this thesis aims to raise a question about the aptitude of the regulatory stability criteria which were in force when that fishing effort control regulation change took place.

There is a general consensus about the idea that the current regulatory frame for intact stability is limited, in the sense that provides the naval architects with technical recipes to design vessels, and assumes the existence of a direct relation between stability and the characteristics of the GZ curve. The problem for designers and supervisors therefore is not to check the stability (ability to remain upright) of a ship on a seaway subject to several heeling moments, but to comply with those criteria. This has some implicit problems:

- First, many other issues, not contemplated in the regulations, affect the ship stability, but designers and regulators simply do not have to consider them. The Severe Wind and Rolling Criterion (Weather Criterion), or the Water on Deck Criterion, added to the regulations much later than the GZ curve criteria, are examples of this idea. These specific dynamic phenomena are not well covered by the existing stability criteria and must be checked separately.

- Second, the GZ curve criteria are of statistic nature (see 1.6), based on the GZ curves of a set of vessels that performed well, but it cannot be ensured that the criteria will provide the same level of safety to fishing vessels with

dimensions or characteristics significantly different from that set of vessels, or that operate quite differently.

Consequently, by simply fulfilling those criteria, immunity against capsizing is not ensured. This idea has explicitly reported in the 2008 IMO Intact Stability Code, Part B, §5.1.1

In this sense, an additional objective of this thesis is exploring the possibility to assess fishing vessels safety –understood as immunity or resistance to capsizing- making use of alternative methodologies that complement or substitute the traditional stability criteria.

Specifically, given that stability in rough weather is a dynamic phenomenon essentially related to vessel motions, this thesis explores the possibility to assess ship safety by means of seakeeping and operability studies. The relationship between operability and safety is investigated.

2.3. Assessment of stability in rough weather

Finally, the thesis aims at studying the stability of the lost vessels by specific rough weather criteria. In this sense, the IMO Weather Criterion and the suitability of some of the Second Generation Intact Stability Criteria (SGISC) under development by IMO to assess fishing vessels stability is studied. Specifically, it is intended to check if the SGISC for the dead ship condition failure mode, in its current status (IMO, 2009), has reached a maturity stage which would make it suitable, in principle, for being used for design purposes. This specific criterion, which is an evolution from the current IMO Weather Criterion, is especially relevant for small fishing vessels. These SGISC are developed from a dynamic and physical approach, moving away from the statistical approach on which classical criteria are based. A priori, this could allow greater precision in forecasting the ship behavior in rough weather. Nevertheless the correct use of this new criteria request greater complexity, a high number of parameters to control and high precision in its application; this inevitably makes uncertainty in their use to rise.

3. METHODOLOGY OF THE THESIS

In order to achieve the objectives exposed in the previous chapter, the thesis studies the five fishing vessels sunk in stability related accidents that were built after the entry into force of the Royal Decree 2287/1998 and compares their main dimensions, stability and operability characteristics with those of the five fishing vessels which were decommissioned to build them, which had themselves entered into service before the approval of that regulation.

The thesis is organized as follows:

First, some basic CFP concepts and the specific Spanish fishing effort control regulations under study are presented.

Then, in order to support the latter statistic calculations the structure of the fishing fleet in Spain regarding vessel size, type of fishing gear or kind of activity is shown.

Third, the five case studies are presented. The five fishing vessels which were decommissioned to build them (predecessors) are selected. The changes to the design characteristics and main dimensions imposed by the new fishing control effort regulations are discussed.

Fourth, the analysis methodologies are described in detail. These are:

- Statistical fishing fleet accident rate
- Regulatory stability
- Operability (seakeeping)
- Stability in rough weather (IMO Weather Criterion and Second Generation Stability Criteria – dead ship condition)

These analyses are applied to the case studies. A first result is the determination of a statistical anomaly in the five accidents under consideration.

After that, the results of the previous analyses applied to each sunk vessel and her respective predecessor are compared.

Analyzing these comparisons case by case and also the observed trends between the two sets of vessels (sunk vessels vs. predecessors) two kind of conclusions are guessed:

- Conclusions about the stability and performance in rough weather of the sunk vessel compared to the predecessors. This is the basis to establish a link

between the change in fishing effort control regulations in Spain, stability and safety.

- Conclusions about the suitability and limitations of some of the methodologies applied in this thesis for the purpose of assessing the stability of fishing vessels in a seaway.

4. FLOODED FISHING VESSELS CASE STUDIES

4.1. General

The case studies are five small fishing vessels that were lost in stability related accidents. Their lengths ranged between 12 and 24 m, and were built shortly after the entry into force of Royal Decree 2287/1998.

As anticipated, between November 2004 and September 2007 these five Spanish-flagged ships capsized due to transversal stability related causes. From the 46 crew members on board of the five vessels, 32 died or were declared missing. Main dimensions and other characteristics of those vessels are presented in Table 6.

Boat code in Spanish fleet	Gear type	Lenth overall (m)	Tonnage (GT)	Year of build	Year of loss	Cause of accident, from the official investigation reports published
25057	Seines	17.00	34.18	2001	2004	Lack of stability; probably surf-riding and broaching
24593	Hook and lines	16.02	29.97	1999	2004	Lack of stability, probably overloading
24391	Seines	18.00	44.83	1999	2004	Lack of stability, probably surf-riding and broaching
24358	Gillnets and entangling nets	20.00	87.03	1999	2006	Lack of stability, probably dead ship condition and fishing spaces flooded
24199	Seines	19.40	59.01	1999	2007	Lack of stability, probably inadequate weight distribution

Table 6. Flooded fishing vessels case studies

The ships in this table are referred to using the SFFR code. The European equivalent to such code is obtained adding to it the country code (ESP in this case) (http://ec.europa.eu/fisheries/fleet/index.cfm?lg=en).

According to the SFFR data, four of the five lost fishing vessels had more than one predecessor. Pursuant to the fishing effort control regime, to build these vessels two or more existing fishing vessels had to be retired from service.

In such cases, the largest vessel has been chosen as predecessor. In all cases the lost vessel and her chosen predecessor share characteristics related to the operations: fishing grounds, gear type and/or base port. This is typical in small fishing industry, where one person –or a group of relatives- owns and operates a vessel. When a

shipowner intends to build a new vessel, normally the working vessel is decommissioned and the gross tonnage excess required to build the new, larger vessel, is completed by acquiring additional smaller units. It is not usual that a shipowner builds a vessel significantly larger than the one he already owns.

The five predecessor vessels were built before Royal Decree 2287/1998 was approved. For the purposes of the present work the vessels are named F1 to F5 (lost vessels) and P1 to P5 (corresponding predecessors). The ten vessels are presented in Table 7 and in the following sections. The bodyplans of the ten vessels are shown (not to scale) in Table 8.

Boat	SFFR code	Boat name	Gear type	Year of build	Length overall (m)	Tonnage (GT)	Notes
F1	25057	NUEVO PILÍN	Seines	2001	17	34.18	Lost vessel
F2	24593	ENRIQUE EL MORICO	Hook and lines	1999	16.02	29.97	Lost vessel
F3	24391	O BAHIA	Seines	1999	18	44.83	Lost vessel
F4	24358	SIEMPRE CASINA	Gilnets / entangling nets	1999	20.5	87.03	Lost vessel
F5	24199	NUEVO PEPITA AURORA	Seines	1999	19.4	59.01	Lost vessel
P1	16060	LETICIA	Seines	1989	15	17.11	Predecessor to 25057
P2	11830	MARIA DOLORES	Hook and lines	1963	11.3	5.86	Predecessor to 24593
P3	5969	AMEIXA	Seines	1978	14.1	28.7	Predecessor to 24391
P4	251	NUEVO HERMANOS CASINA	Gilnets / entangling nets	1983	16	47	Predecessor to 24358
P5	5154	PEPITA LA AURORA	Seines	1959	15.75	29	Predecessor to 24199

Table 7. Fishing vessels case studies – lost vessels and predecessors

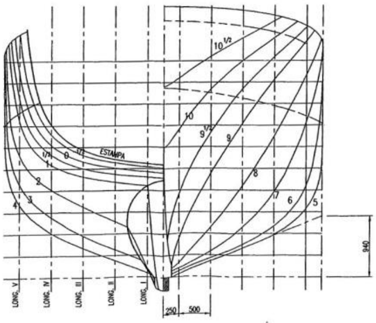
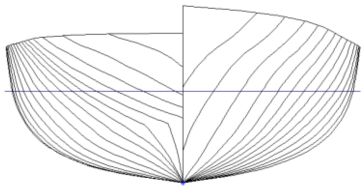
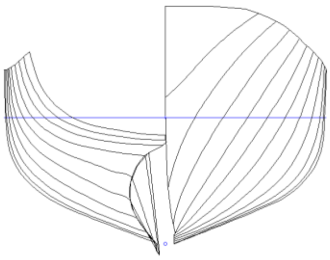
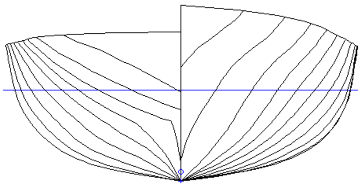
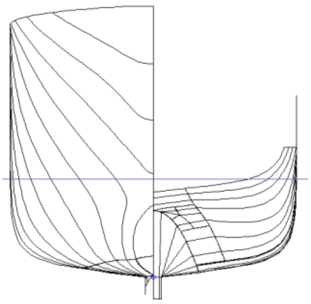
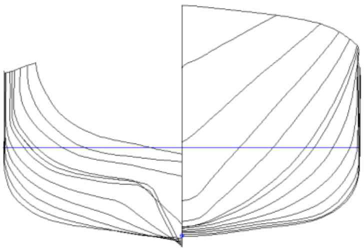
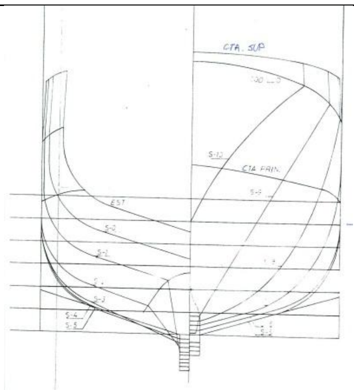
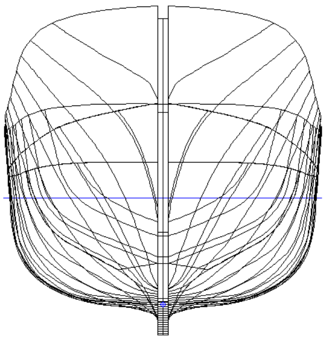
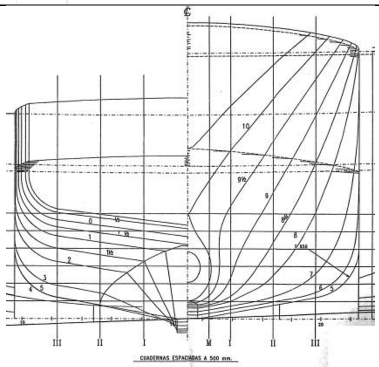
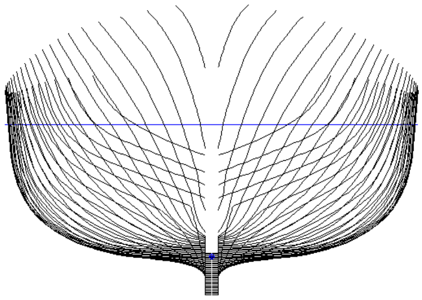
	Fishing vessels (F1 to F5)	Predecessors (P1 to P5)
F1-P1		
F2-P2		
F3-P3		
F4-P4		
F5-P5		

Table 8. Fishing vessels body plans

It has not been possible to obtain precise information about all predecessors, for the following reasons:

- Some documents are missing in the ship file or there is not ship file in the Spanish Maritime Administration, as some vessels are quite old.
- Some documents were not compulsory by the regulation that was in force when some of the predecessors were built (e.g. hullform plan, stability book…)
- The shipyards where some boats were built do not exist nowadays or do not keep files of those boats.

Due to these reasons, not all the main dimensions and characteristics of these vessels were available. Some of them had to be estimated according to the following procedures:

- Hullforms were obtained by linear transformation of known similar fishing vessels. The vessels from which the studied ones were obtained had similar dimensions, the same type of fishing gear, hull material, and hull type (stern and bow). When possible, ships built in close years and from the same areas were chosen.
- Unknown main dimensions have been estimated by linear regression of databases of fishing vessels, similar in size, type of fishing gear, year of built, hull material and area of operation.

For each of the ten fishing studied a characteristic loading condition is established. Each vessel has been studied in one loading condition only, chosen from the information available, normally the full load condition. In the case of vessels for which no stability booklets were available (most predecessors) a loading condition close to the full load is estimated, with the best information available.

The natural roll period included in the following tables has been estimated using the formulae:

$$T_0 = 2\pi \cdot \sqrt{\frac{J_{xx} + J_{add}}{\Delta \cdot GM}} \qquad (1)$$

Where

- Δ is the ship displacement
- GM is the metacentric height
- J_{xx} is the ship moment of inertia in air

- J_{add} is the added moment of inertia

The above magnitudes are obtained for the given loading condition. The moments of inertia are computed by the linear seakeeping program PRECAL according to section 5.4.1

4.2. Vessels F1 (25057 – NUEVO PILIN) and P1 (16060 – LETICIA)

On 19th November 2004 the purse seiner NUEVO PILIN sunk with five crewmembers on board in the Cantabric Sea. Three persons died and two disappeared. The cause of the accident was the loss of transversal stability, which caused the vessel to capsize (CPISM, 2010a).

The F/V NUEVO PILÍN was a seiner with base port in Santoña (Cantabria), with licence to fish in the NW Cantabric fishery. Her main dimensions are shown in Table 9.

The vessel was built in 2001 and her building approval required two existing fishing vessels to be decommissioned. F/V LETICIA, the largest of these two, shares with vessel 25057 the base port, fishing gear and fishing ground.

A comparison between these two vessels main dimensions shows the following facts:

- While both vessels have lengths and breadths similar in magnitude, F1 has almost three times the displacement of P1. This is achieved mostly by increasing draught by a factor of 2.
- F1 has twice as tonnage as P1, while their displacement ratio is close to 2.8. The new ship has a lower tonnage to displacement ratio. That is to say, in the new vessel the useful volume has moved upwards.
- F1 freeboard is half the freeboard of P1.

Figure 6. Fishing vessels F1 (left) and P1 (right) (source: SFFR)

Boat code	F1	P1	F1/V1
Name	NUEVO PILÍN	LETICIA	-
SFFR boat code	25057	16060	-
Year of build	2001	1989	-
Year of loss / retirement	2004	2001	-
Base port	SANTOÑA	SANTOÑA	-
Fishing ground	Cantabric-northwest	Cantabric-northwest	-
Main gear	Seines	Seines	-
Hull material	Steel	Wood	-
Length overall (m)	17	15	1.1
Length bet. perp. (m)	13.5	12.6	1.1
Breadth (m)	5	4.08	1.2
Depth to main deck (m)	2.35	1.54	1.5
Mean Draught (m)	2.127	1.05	2.0
Displacement (t)	71.2	25.0	2.8
Freeboard (m)	0.223	0.49	0.5
Gross Register Tons (GRT)	30.15	13.37	2.3
Gross tonnage (GT)	34.18	17.11	2.0
Tonnage volume (m^3)	140.7	68.5	2.1
Enclosed volume below main deck (m^3)	85.32	52.50	1.6
Enclosed volume over main deck (m^3)	55.38	16	3.5
Ratio Volume over / Volume below deck	0.649	0.305	2.1
Ratio freeboard / Breadth	0.045	0.12	0.38
Propulsive power (kw)	168	136	1.2
Centre of gravity height over base line (KG - m)	2.191	1.185	1.85
Transversal metacentric height (GM – m)	0.579	0.842	0.69
Natural roll period (s)	5.2	3.3	1.57

Table 9. Vessels F1 and P1

4.3. Vessels F2 (24593 – ENRIQUE EL MORICO) and P2 (11830 – MARIA DOLORES)

In August 2004 the longliner ENRIQUE EL MORICO capsized after being hit by several waves, while navigating in rough weather. All the crewmembers were rescued safe except the skipper, who disappeared when the vessel capsized. The cause of the accident was the loss of transversal stability, possibly caused by overloading and an incorrect distribution of weight on board (CPISM, 2010b). The F/V ENRIQUE EL MORICO was a liner with base port in Adra (Almería) with licence to fish in the Mediterranean Sea. At the moment of her accident was operating as a pot vessel.

The vessel was built in 1999 and one existing vessel had to be decommissioned to get the build approval. The vessel decommissioned was the F/V MARIA DOLORES, a liner with the same base port built in wood. F2 is shown in Figure 7. There are no images of vessel P2. The dimensions and characteristics of both vessels are shown in Table 10.

No reliable data for the depth to main deck in F2 could be found; therefore it has been estimated from linear regressions in a set of similar vessels. The stability and operability calculations presented in chapter 6 are performed with the draft and freeboard included in Table 10.

Figure 7. Fishing vessel F2 (source: SFFR)

Boat code	F2	P2	F2/V2
Name	ENRIQUE EL MORICO	MARIA DOLORES	-
SFFR boat code	24593	11830	-
Year of build	1999	1963	-
Year of loss / retirement	2004	2000	-
Base port	Adra (Almería)	Adra (Almería)	-
Fishing ground	Mediterranean	Mediterranean	-
Main gear	Hook and lines (operating as pot vessel)	Hook and lines	-
Hull material	Glass fibre reinforced plastic	Wood	-
Length overall (m)	16.02	11.3	1.4
Length bet. perp. (m)	13.8	9.5	1.5
Breadth (m)	4.57	4.38 (*)	1.0
Depth to main deck (m)	2.15 (*)	1.57 (*)	1.4
Mean Draught (m)	1.8	1.17 (**)	1.5
Displacement (t)	53.23	21.653	2.5
Freeboard (m)	0.658	0.4 (*)	1.6
Gross Register Tons (GRT)	26.03	10.1	2.6
Gross tonnage (GT)	29.97	5.86	5.1
Tonnage volume (m^3)	123.91	Data not available	-
Enclosed volume below main deck (m^3)	58.52	Data not available	-
Enclosed volume over main deck (m^3)	65.4	Data not available	-
Ratio Volume over / Volume below deck	1.12	0.64 (***)	1.7
Ratio freeboard / Breadth	0.14	0.092	1.5
Propulsive power (kw)	319	115	2.8
Centre of gravity height over base line (KG - m)	1.8	1.334	1.3
Transversal metacentric height (GM – m)	0.68	0.93	0.7
Natural roll period (s)	4.4	3.5	1.26

Table 10. Vessels F2 and P2

(*) estimated from linear regressions in similar vessels for which data are available
(**) calculated as depth to main deck minus freeboard
(***) mean value in vessels of similar age and fishing gear

4.4. Vessels F3 (24391 – O BAHIA) and P3 (5969 – AMEIXA)

The fishing vessel O BAHIA was lost in June 2004 while navigating in rough weather close to the Galician coast, with 10 people on board. All of them died or disappeared. The investigation determined that the vessel capsized for loss of stability navigating in following seas (CPISM, 2010c). She could have experienced some dangerous dynamic phenomena as surf riding, and pure loss of stability in following waves.

The F/V O BAHIA was a purse seiner with base port in Cambados (Pontevedra) and operated in the waters around Galicia. For building her the seiner AMEIXA, with same base port, fishing ground and gear type, had to be decommissioned after 22 years of service. The vessels are shown in Figure 8. The dimensions and characteristics of both vessels are shown in Table 11.

Due to the variety of sources of information for gathering the main data of the F3 vessel, some inconsistencies were found in the value of depth to main deck for the F3 vessel. A possible explanation could be that the depth is measured with reference to a point below the vessel base line, e.g., the keel lower side.The stability and operability calculations presented in chapter 6 are performed with the draft and freeboard included in Table 11.

Figure 8. Fishing vessels F3 (left) and P3 (right) (source: SFFR)

Boat code	**F3**	**P3**	**F3/V3**
Name	O BAHIA	AMEIXA	-
SFFR boat code	24391	5969	-
Year of build	1999	1978	-
Year of loss / retirement	2004	2000	-
Base port	Cambados (Pontevedra)	Cambados (Pontevedra)	-
Fishing ground	Cantabric-northwest	Cantabric-northwest	-
Main gear	Seines	Seines	-
Hull material	Steel	Wood	-
Length overall (m)	18	14.1	1.3
Length bet. perp. (m)	13.5	12.5	1.1
Breadth (m)	5.2	5.12	1.0
Depth to main deck (m)	2.35 (*)	1.7	1.4
Mean Draught (m)	1.775	1.264	1.4
Displacement (t)	80.67	43.6	1.9
Freeboard (m)	0.336	0.436	0.8
Gross Register Tons (GRT)	23.69	26.4	0.8
Gross tonnage (GT)	44.83	28.7	1.6
Tonnage volume (m^3)	182.8	102.7	1.8
Enclosed volume below main deck (m^3)	122.6	78.44	1.6
Enclosed volume over main deck (m^3)	60.2	24.26	2.5
Ratio Volume over / Volume below deck	0.491	0.309	1.6
Ratio freeboard / Breadth	0.065	0.09	0.76
Propulsive power (kw)	290	250	1.2
Centre of gravity height over base line (KG - m)	2.21	1.56	1.4
Transversal metacentric height (GM – m)	0.76	1.38	0.55
Natural roll period (s)	4.8	3.3	1.45

Table 11. Vessels F3 and P3

4.5. Vessels F4 (24358 – SIEMPRE CASINA) and P4 (251 – SIEMPRE HERMANOS CASINA)

In February 2005 the fishing vessel SIEMPRE CASINA capsized in waters of the Cantabric Sea while navigating in rough weather with 9 persons on board. As a consequence, eight of the crewmembers died or disappeared. The vessel did not sink and could be recovered. The investigation determined that the loss of stability after the flooding of inner spaces through open doors on the stern above the freeboard deck caused the accident (CPISM, 2010d).

For building her, the F/V NUEVO HERMANOS CASINA was decommissioned. She was a smaller vessel with the same fishing grounds, base port and gear type. Both vessels are shown in Figure 9 and their characteristics are listed in Table 12.

Figure 9. Fishing vessels F4 (left) and P4 (right) (source: SFFR)

Boat code	F4	P4	F4/V4
Name	SIEMPRE CASINA	NUEVO HERMANOS CASINA	-
SFFR boat code	24358	251	-
Year of build	1999	1983	-
Year of loss / retirement	2006	2000	-
Base port	Burela (Lugo)	Burela (Lugo)	-
Fishing ground	Cantabric-northwest	Cantabric-northwest	-
Main gear	Gillnets / entangling nets	Gillnets / entangling nets	-
Hull material	Steel	Wood	-
Length overall (m)	20.5	16	1.3
Length bet. perp. (m)	16.2	14.46	1.1
Breadth (m)	5.3	4.7	1.1
Depth to main deck (m)	2.3	1.902	1.2
Mean Draught (m)	2	1.302	1.5
Displacement (t)	97.82	49.2	2.0
Freeboard (m)	0.300	0.600	0.5
Gross Register Tons (GRT)	34.46	20.0	1.7
Gross tonnage (GT)	87.0	47.0	1.9
Tonnage volume (m^3)	347.0	174.4	2.0
Enclosed volume below main deck (m^3)	139.3	114.8	1.2
Enclosed volume over main deck (m^3)	207.7	59.6	3.5
Ratio Volume over / Volume below deck	1.49	10.52	2.9
Ratio freeboard / Breadth	0.06	0.13	0.44
Propulsive power (kw)	160	128	1.28
Centre of gravity height over base line (KG - m)	2.238	1.98	1.1
Transversal metacentric height (GM – m)	0.62	1.1	0.56
Natural roll period (s)	4.3	3.3	1.30

Table 12. Vessels F4 and P4

4.6. Vessels F5 (24199 – NUEVO PEPITA AURORA) and P1 (5154 – PEPITA LA AURORA)

The F/V NUEVO PEPITA AURORA was a seiner built in 1999 in steel, with base port in Barbate (Cádiz) and license to fish in the Gulf of Cádiz. For approving her building, F/V PEPITA LA AURORA was decommissioned. This was a wooden seiner built in 1959 which operated in the Gulf of Cádiz as well.

The F/V NUEVO PEPITA AURORA capsized and sunk while navigating in rough weather with sixteen persons on board. As a consequence, eight of the crewmembers died or disappeared. The investigation determined that the vessel had a permanent list and was hit by several waves that embarked water and caused her to capsize (CPISM, 2010e).

The main dimensions and characteristics of both vessels are listed in Table 13.

As in previous cases, it is significant that the nominal propulsive power in both vessels is almost the same, while F5 displacement is significantly higher than P5’s.

Figure 10. Fishing vessels F5 (left) and P5 (right) (source: SFFR)

Boat code	F5	P5	F5/V5
Name	NUEVO PEPITA AURORA	PEPITA LA AURORA	-
SFFR boat code	24199	5154	-
Year of build	1999	1959	-
Year of loss / retirement	2007	1999	-
Base port	Barbate (Cádiz)	Sanlúcar de Barrameda (Cádiz)	-
Fishing ground	Golfo de Cádiz	Golfo de Cádiz	-
Main gear	Seines	Seines	-
Hull material	Steel	Wood	-
Length overall (m)	19.4	15.75	1.2
Length bet. perp. (m)	15.5	14.0	1.1
Breadth (m)	5.75	5.0	1.2
Depth to main deck (m)	2.5	2.068	1.2
Mean Draught (m)	1.73	1.61	1.1
Displacement (t)	90.77	68.14	1.3
Freeboard (m)	0.77	0.458	1.7
Gross Register Tons (GRT)	32.45	32.45	1.0
Gross tonnage (GT)	59.0	29.0	2.0
Tonnage volume (m^3)	238.4	120.04	2.0
Enclosed volume below main deck (m^3)	159.0	-	-
Enclosed volume over main deck (m^3)	79.4	-	-
Ratio Volume over / Volume below deck	0.5	-	-
Ratio freeboard / Breadth	0.13	0.09	1.5
Propulsive power (kw)	270	275	
Centre of gravity height over base line (KG - m)	2.17	1.104	2.0
Transversal metacentric height (GM – m)	0.96	1.2	0.8
Natural roll period (s)	4.8	3.4	1.41

Table 13. Vessels F5 and P5

4.7.Comparison between lost vessels and predecessors

Analyzing the previous tables, in all the case studies, a relative increase of the ratio between the volume above and below the tonnage deck can be seen. This is reflected in the value of the ratio of V1/V2 being substantially larger for the analyzed vessels than for their predecessors. These volume distributions, chosen by the ship designers, are consistent with the possibilities offered by the 1998 fishing effort control regulation, as discussed in section 1.2. This increase of the volume above main deck implies higher weights and more lateral area exposed to the wind; both issues penalize marginal stability.

It is relevant to mention that for case studies 1, 3 and 5, the GT ratios and the ratios V1/V2 between each ship and its predecessor are very similar. This implies that the GT increase is obtained in those cases by increasing the closed volumes above the tonnage deck. These vessels belong all to the seiner type. In both other cases, the changes in design were not so evident.

A significant reduction in the ratio between freeboard and breadth is present in four out of the five case studies (apart from fishing vessel F5-24199, with a significant freeboard increase). This freeboard reduction, which penalizes safety margins in regards to green water events, was expected, as anticipated in section 1.2, as a response from the designers to the challenge offered by the extra weight above waterdeck due to the extra volume present there.

Finally, a significant GM reduction is present in four out of the five cases (apart from vessel F5-24199, with a slight reduction but remaining far above the minimum value of 0.35 m established by the stability rules). It has to be kept in mind that the GM is the main initial stability indicator. The reduction in GM implies a reduction in the stability criteria fulfillment margins with respect to their predecessors. Therefore, and although being within the requirements of the IMO for intact stability, the marginal stability of the new designs was significantly smaller than that of the predecessors. In addition to this factor, the new vessels were going to be operated by the same people and in the same conditions as their predecessors, and we can guess that these crews possibly ignored this issue.

5. DESCRIPTION OF THE PERFORMED ANALISES

5.1. General

In this chapter a thorough description of the statistical analysis performed and the regulatory stability, seakeeping and stability in rough weather methodologies applied is presented.

5.2. Fishing fleet accident rate assessment

In order to detect abnormal concentrations of accidents within a specific group of a population, inequality analysis is a widespread tool. It is mainly used in health sciences (Brown, 1994) but it has also been applied to the analysis of fishing accidents (Perez-Labajos et al., 2006, 2009). Due to the strong evidence found, a simpler approach is followed here in order to establish the statistical anomaly of the case studies considered.

The joint probability of occurrence of the five accidents has been estimated by standard statistical analyses (see section 6.1.2) applied over the following databases:

a) Spanish Fishing Fleet Register (SFFR). This database is maintained by the Spanish Ministry for Agriculture, Food and Environment (MAGRAMA). It contains records of most fishing vessels registered in Spain between 1870 and 2003. A total of 27190 fishing vessels are recorded. For each vessel many data as length, type of gear, tonnage, base port and status are stored. In the field dedicated to the vessel status, in the event that a vessel has been lost in an accident, the cause of the accident is recorded. The only types of accident recorded in the database are:

    - Fire,
    - Collision,
    - Foundering (water ingress in general)

    Therefore, when a vessel has sunk in an accident, for causes different from fire or collision, the vessel status is included in the generic "foundering".

b) CIAIM marine accidents database. The Spanish Maritime Accident and Incident Investigation Standing Commission (CIAIM) is the competent body in the investigation of maritime accidents in Spain. CIAIM publishes accident reports as well as annual reports with accident statistics on its site

(http://www.ciaim.es). The CIAIM database stores the causes of marine accidents occurred in Spain since October 2008. The type of accidents recorded in this database are:

- Capsizing / listing
- Collision (with another ship)
- Contact (with floating or fixed object other than a ship)
- Damage to ship or equipment
- Grounding / stranding
- Fire / explosion
- Flooding / foundering
- Loss of control (propulsion / directional / electrical power / containment)
- Hull failure
- Missing (cause unknown)

5.3.Regulatory stability

The vessels stability is checked against some of the IMO stability criteria for fishing vessels proposed in the the «Code on intact stability for all types of ships covered by IMO instruments», approved by the IMO Assembly Resolution A.749(18). These criteria are presented in Table 14.

Criterion	Magnitude to check	Criterion type	Limiting value
C1	Area under GZ curve between 0º and 30º	Not less than	0.055 rad.m
C2	Area under GZ curve between 0º and 40º or flooding angle	Not less than	0.090 rad.m
C3	Area under GZ curve between 30º and 40º or flooding angle	Not less than	0.030 rad.m
C4	GZ at a heeling angle of 30º or more	Not less than	200 mm
C5	Heel angle corresponding to maximum GZ	Not less than	25º
C6	Initial metacentric height (GMo).	Not less than	350 mm

Table 14. IMO stability criteria

Spain had adopted those stability criteria which were in force when the five lost vessels under study were designed and built. The IMO Severe Wind and Rolling Criterion (Weather Criterion) has not been considered in the present section, as it was not mandatory when the five predecessors were built. Regarding the five lost vessels, according to the Spanish stability regulations, compliance with the Weather Criterion has to be checked only if the area under the stability curve up to 30º is below 0.065 m rad in the most unfavorable loading condition. This condition was fulfilled by the five vessels concerned, so Weather Criterion had not to be checked.

Stability calculations have been performed with state-of-the-art naval architecture software (Hydromax), with free trim. No free surfaces in tanks are considered. The center of gravity is considered to be amidships. For the cases where the stability booklet is available small differences are found between the calculated cross-curves and the ones in the booklet. These differences are mainly attributed to the hull modeling process to introduce hull form data into the naval architecture software.

For each ship the stability curves in the studied loading condition are obtained.

5.3.1. Stability index

Stability curves give a quick and good idea of the stability characteristics of a vessel, and noticeable differences are found between the stability curves of some of the vessels. These differences may be quantified by comparing each single stability criterion under Table 14. However, for comparison purposes it is convenient to establish a single magnitude to better quantify the differences in regulatory stability between each fishing vessel and her predecessor.

Thus, a global index is developed. For each vessel the largest KG for which all the stability criteria in Table 14 are fulfilled is computed; this is defined as the Limiting KG. Then, the stability index (SI) for comparison for each vessel is the ratio between the Limiting KG and the actual KG of the loading condition studied. This SI is presented in percentage terms, and gives an idea of the reserve of stability of the vessel:

$$SI \quad stability\ index \ = \frac{Limiting\ KG - Actual\ loading\ condition\ KG}{Actual\ loading\ condition\ KG}\ \% \qquad (2)$$

5.4. Seakeeping and operability

5.4.1. General

As anticipated in the previous chapters, the current stability criteria might not properly cover part of the dynamic phenomena present in several stability related accidents, and some authors propose to explore the link between operability and stability to assess vessel safety. In order to discuss operability, the seakeeping performance of the ten vessels has been analyzed. A short-term seakeeping analysis, checking ship motions against a series of criterion limiting the ship operability, has been performed. According to Tello et al. (Tello et al., 2011) the following criteria can be used to assess fishing vessels operability:

- Probability of green water on deck not higher than 5%
- Slamming probability not higher than 3%
- Propeller emergence probability not higher than 15%
- Vertical acceleration at work deck / bridge not higher than 0.2 g (rms)
- Lateral acceleration at work deck / bridge not higher than 0.1 g (rms)
- Roll not higher than 6º (rms)
- Pitch not higher than 3º (rms)

Slamming may be argued to be more connected to operability than to safety, therefore for the purpose of this work, it has not been considered. For the operability analysis performed the criteria used are listed in Table 15:

Criterion	Prescribed value
Green water on deck (at working deck fore and working deck aft)	5% (probability)
Propeller emergence	15% (probability)
Vertical acceleration (at bridge, working deck fore and working deck aft)	0.2 g (rms)
Lateral acceleration (at the previous three points)	0.1 g (rms)
Roll	6º (rms)
Pitch	3º (rms)

Table 15. Operability criteria

Motions response amplitude operators (RAOs) have been calculated using the PRECAL linear seakeeping code. PRECAL computes ship motions in frequency domain using a 3D panel boundary element method formulation (Chow and McTaggart, 1996; "PRECAL version 6.6 User Manual," 2010).

A dimensionless linear equivalent roll damping coefficient of 0.12 has been considered for the roll motion, akin to the value chosen by Tello et al. (Tello et al., 2011), considering that same types of vessels are under analysis in our research.

The x, y, z inertia radius ratios versus breadth (B), length between perpendiculars (Lbp) and Lbp, respectively have been estimated by the PRECAL code by the following formulae:

$$K_{roll} = 0.289 \cdot B \cdot \sqrt{1.0 + 0.4 \cdot \left(\frac{Kg}{B}\right)^2} \tag{3}$$

$$K_{pitch} = 0.25 \cdot Lbp \tag{4}$$

$$K_{yaw} = \sqrt{K_{roll}^2 + K_{pitch}^2} \tag{5}$$

Where

- B is the ship breadth
- Kg is the center of gravity height over the base line
- Lbp is the length between perpendiculars

The inertia radii take values between 0.32 and 0.38 for roll, 0.25 for pitch, and between 0.27 and 0.29 for yaw. These latter values are similar to the ones used by Tello et al. (0.4, 0.25 and 0.25 respectively).

Added mass and added inertia are computed by PRECAL.

Green water on deck and propeller emergence probabilities have been computed according to the formulation given by Lloyd (Lloyd, 1989), on the basis of the relative motions between the vessel and the sea surface given by the seakeeping code. In this context, “probability” is defined as the probability of the local relative motion exceeding a given value: the distance to the bulwark (green water), the effective draught (slamming) or the propeller immersion (propeller emergence). It is assumed that the local relative motion to the sea surface is closely approximated by the Rayleigh distribution. According to this model, the probability is estimated by

$$P_{episodic\ motion} = \exp(-\frac{1}{2}\frac{D^2}{C_s^2 m_0}) \tag{6}$$

Where

- D is the vertical distance from the calm surface to the point where the probability is calculated.
- m_0 is the variance of the notional relative motion at the appropriate location on the ship.
- Cs is a "swell up coefficient" defined as the ratio of the actual relative motion amplitude to the notional relative motion amplitude. For convenience, this coefficient is taken equal to 1.

For the green water on deck criterion the probability of water shipment has been calculated in two points for each vessel: at deck level fore and aft and the higher value is chosen.

Vertical and lateral accelerations have been computed in three points in each vessel: at the working deck (fore and aft), and at the bridge. The largest value amongst the three ones is chosen for checking the criterion fulfillment.

Calculations have been performed for headings 0º (following seas) to 180º (head seas) in steps of 30º and vessel speed from 0 to 10 knots in steps of 2 knots.

Although the proposed criteria limit operability and not safety, strictly speaking, and therefore larger values of the criteria could be accepted, it is assumed that, for comparative purposes, the used values could be valid indicators of the vessels safety.

However, it is necessary to be aware of the several limitations of the method used, as linear seakeeping cannot capture some dynamic phenomena in waves –e.g., broaching-to or parametric rolling-, and the amplitude of the ship motions in large amplitude waves can be questioned. These limitations must be taken into account when considering the relationship between the calculated operability and ship safety.

In addition, it is important to stress that linear seakeeping calculations may present problems in case of following seas when the frequency of encounter becomes close to zero.

5.4.2. Sea state

The operability study has been performed in two sea conditions defined by the significant wave height and modal wave period according to the standardized scale adopted by NATO (Military Agency for Standarization, NATO, 1983). For all vessels

SSN4 and SSN5 have been studied, corresponding to a significant wave height of 1.88 and 3.25m with modal periods of 8.8 and 9.7 s, respectively.

A Bretschneider or two parameter Pierson-Moskowitz sea spectrum has been used. The spectrum of the wave elevation S_{zz} is a function of the wave circular frequency ω (rad/s) and has the following expression:

$$S_{zz}(w) = \frac{H_s^2}{4 \cdot \pi} \cdot \left(\frac{2 \cdot \pi}{T_z}\right)^4 \cdot w^{-5} \cdot \exp\left(-\frac{1}{\pi} \cdot \left(\frac{2 \cdot \pi}{T_z}\right)^4 \cdot w^{-4}\right) \quad (7)$$

Where H_s is the significant wave height and T_z the zero crossing period.

Three of the five studied vessels were lost in the Atlantic Ocean, close to the Spanish north coast; one sank in the Gulf of Cadiz, close to Gibraltar strait, while the fifth was lost in the Mediterranean Sea. Those sea states chosen have been found to fairly represent the conditions of those areas, where the fleet of small coastal fishing vessels operates most of the time. With the RAOs obtained with PRECAL and the previously mentioned spectra, the motion spectra have been computed and used to obtain the rms (root mean square) values necessary to assess the fulfillment of the operability criteria presented in Table 15.

5.4.3. Operability index

For comparative purposes an operability index (OI) has been defined, calculated as the fraction of combinations speed-heading at which the vessel operates complying with all operability criteria. The OI may be formally established using an auxiliary function Z which depends on speed and heading. Defining Z as a Boolean function which takes the value 1 when at least one criterion is surpassed and 0 for the safe zone:

$$OI = 1 - \int_0^{\pi} \int_0^{10} z(\theta, v)\, dv \cdot d\theta \,/(10\pi) \quad (8)$$

An OI equal to zero means that at least one operability criterion is surpassed for every combination of ship speed and heading. If OI equals 1 the vessel operates safely in any speed and heading, without surpassing any criterion.

Operability indexes have been obtained for the five pairs of studied ships and their predecessors for the speeds from 0 to 10 knots in steps of 2 knots and headings from 0 degrees (following seas) to 180 degrees (head seas) in step of 30 degrees. The values of the operability indexes have been interpolated for those points lying inside the intervals defined. This approach is necessary to obtain accurate operability graphs and

hence meaningful OIs. The loading conditions studied are the same as in the stability study.

5.5. Stability in rough weather

5.5.1. General

While the stability criteria studied in the previous section allows comparing the stability evolution according to the regulations in force applicable to the vessels considered, the criteria considered do not reliably represent the safety levels when navigating in rough weather.

Consequently, the compliance with *ad-hoc* rough weather stability criteria has been checked, even though it was not compulsory under the stability regulations in force when the ten studied vessels were built.

Two specific rough weather criteria have been studied:

- Severe Wind and Rolling Criterion (Weather Criterion) established by IMO Resolution A.562(14)
- Stability in dead ship condition, according to the methodology proposed by Bulian and Francescutto (Bulian and Francescutto, 2006, 2004). This methodology is the basis of a proposal for the Second Generation Intact Stability Criteria (SGISC) in dead ship condition.

5.5.2. Weather Criterion

The Severe Wind and Rolling Criterion (Weather Criterion) is one of general provisions of the IMO 2008 Intact Stability Code. This criterion was originally developed to guarantee the safety against capsizing for a ship losing all propulsive and steering power in severe wind and waves, which is known as a dead ship condition.

This criterion is well known and explanatory notes have been developed by IMO explaining the fundamentals behind the criterion (IMO, 2008), the underlying physical laws and the implicit assumptions.

The basic principle of the weather criteria is an energy balance between the beam wind heeling and righting moments with a roll motion taken into account. A graphical representation of this criterion is shown in Figure 11. The underlying physical ideas behind the criterion are:

- The ship is assumed to be heeled under the action of a steady beam wind providing a constant, heel independent, heeling moment;

- In addition, the ship is assumed to roll (mainly due to the action of waves) around the equilibrium angle under the action of constant beam wind with amplitude determined according to the criterion.
- When the ship is at the maximum heel to the windward side, a gust occurs leading to a wind heeling moment that is 50% higher than the heeling moment due to the steady wind.
- The ship is required to have sufficient "dynamic stability" to "survive" the considered scenario. This will occur if b (Figure 11) is larger than a. Otherwise the vessel will reach the capsizing angle φ_2.

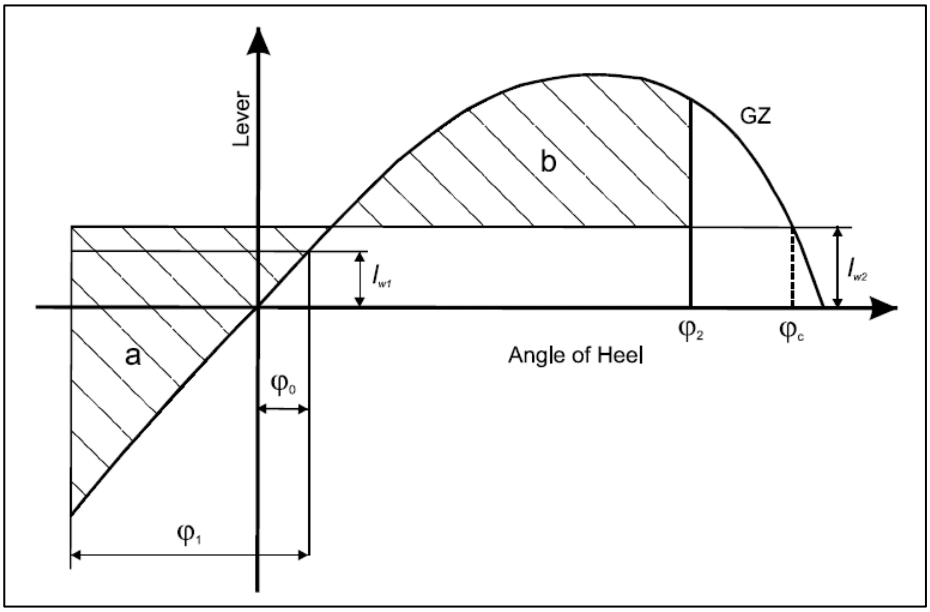


Figure 11. Graphical representation of the Weather Criterion

For vessels with length below 24 m this criterion was introduced into the Spanish legislation by Royal Decree 543/2007. Under this regulation, the criterion is fulfilled if

$b \geq a$, see Figure 11,

where

- φ_2 = min {φ_f, 50º, φ_c}
- φ_f = heel angle of progressive flooding.
- φ_o = heel angle due to steady wind moment

- b = area under the righting lever curve limited by the wind gust heeling lever curve, up to the angle φ_2.

- a = area over the righting lever curve limited by the wind gust heeling lever, from the angle of maximum heel to the windward side.

According to this regulation, when the area below GZ curve up to 30 degrees of a fishing vessel with L < 24 m, is smaller than 0.065, compliance with the above Weather Criterion must be ensured.

5.5.3. Dead ship condition (2nd Generation Stability Criteria)

As explained in the previous section, Weather Criterion is based on partially semi-empirical approaches. To overcome the inherent limitations to this criterion, a Second Generation Intact Stability Criteria (SGISC) for dead ship condition is under development by IMO.

Some authors (Bulian and Francescutto, 2006) have proposed a methodology to assess the ship vulnerability to the failure mode "dead ship condition". Under this approach vulnerability is assessed by estimating the short term probability of capsizing by calculating the roll motion under the combined action of stochastic wind and waves.

This is the basis of the methodology agreed by SLF for the 2nd tier vulnerability criteria for the dead ship condition (IMO, 2013). The probability of capsizing is estimated following the methodology by Bulian and Francescutto with some modifications which are explained hereinafter.

A brief explanation of the methodology used, extracted from the IMO literature (IMO, 2013) and the works from Bulian and Francescutto (Bulian and Francescutto, 2006, 2004) follows. Most of the text and formulae included in this section is taken directly from these references. This section is not intended to be a thorough description of the methodology, and further details and explanations may be found in the referenced documents by Buliand and Francescutto (Bulian and Francescutto, 2006, 2004) and IMO (IMO, 2013).

A conceptual scheme of the assumed underlying simplified physical modelling of the phenomenon is shown in Figure 12.

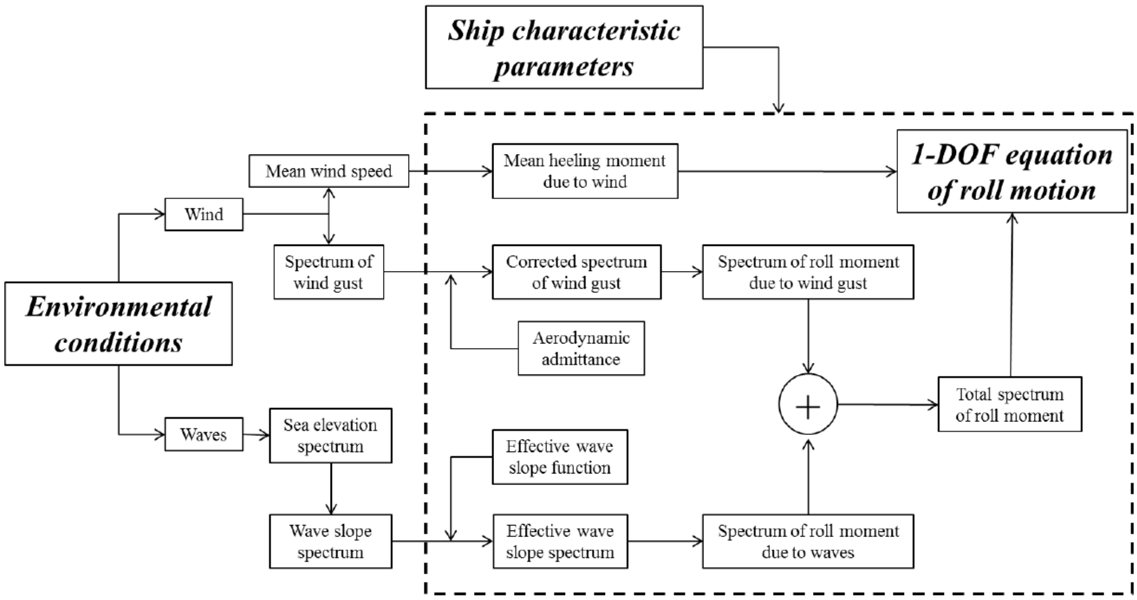


Figure 12. Conceptual scheme of the assumed simplified physical modelling for the short-term assessment (source: IMO)

The objective of this analysis is obtaining a short-term capsize index Cs by means of a simplified calculation methodology which takes into account the roll dynamics in given environmental conditions. The fundamental set of assumptions underlying is as follows:

1. the ship is assumed to be in dead-ship condition in irregular waves and gusty wind for a specified exposure time;
2. wind and waves are assumed to blow/propagate in the same direction and water depth is assumed to be infinite;
3. the ship is assumed to remain beam to wind and waves;
4. the wind state is characterized by a mean wind speed and a gustiness spectrum;
5. the sea state is characterized by a wave elevation spectrum and waves are assumed to be long crested; and
6. the roll motion of the vessel is modelled as a one-degree of freedom (1-DOF) system.

The roll motion of the ship is described by the following 1-DOF non-linear model:

$$(J_{xx} + J_{add}) \cdot \varphi + D(\varphi) + \Delta \cdot GZ(\varphi) = M_{wind,tot}(\varphi, t) + M_{waves}(t) \qquad (9)$$

Where

- J_{xx} is the ship dry moment of inertia
- J_{add} is the added moment of inertia
- D(φ’) is the general damping moment
- Δ is the ship displacement
- GZ(φ) is the restoring lever
- $M_{wind,tot}$(φ,t) is the total instantaneous moment due to wind taking
- M_{waves}(t) is the total instantaneous moment due to waves

For simplicity, a linear roll damping model is chosen, therefore D(φ’) = 2·µ·φ’, with

$$\mu = k \cdot \sqrt{(J_{xx} + J_{add}) \cdot GM \cdot \Delta} \qquad (10)$$

where GM is the transversal metacentric height and k a non-dimensional damping coefficient. Following Tello et al. (Tello et al., 2011) the coefficient k may be taken constant for fishing vessels similar to the studied, equal to 0.12.

By dividing equation (9) by (J_{xx}+J_{add}) it can be rewritten as

$$\varphi + 2\mu \cdot \varphi + w_0^2 \cdot GZ(\varphi)/GM = w_0^2 \cdot (m_{wind,tot}(\varphi, t) + m_{waves}(t)) \qquad (11)$$

The restoring lever GZ(φ) is obtained from standard hydrostatic software.

Added inertia is computed using PRECAL linear seakeeping software, for each vessel, at zero speed.

Moment of waves

Spectrum of wave moment has been obtained by two different methods:

1. Moment of waves is directly computed by the PRECAL software. PRECAL is a state-of-the-art linear seakeeping software that calculates wave loads and vessel motions in regular waves, on the basis of three dimensional potential theory ("PRECAL version 6.6 User Manual," 2010). To avoid problems associated with roll-sway-yaw coupling in the 1-dof roll model only Froude-Krylov moments are considered for the calculations.

2. The spectrum of wave moment is estimated according to the methodology by Bulian and Francescutto. Under this assumption, the excitation moment due to waves M_{waves} is assumed to be a Gaussian process, whose spectrum, $SM_{waves}(\omega)$ is estimated from the sea wave slope spectrum $S_{\alpha\alpha}(\omega)$:

$$S_{M_{waves}}\ w\ = (\Delta \cdot GM \cdot f_{r,waves}(w))^2 \cdot S_{\alpha\alpha}(w) \qquad (12)$$

Where $f_{r,waves}(\omega)$ is the effective wave slope function and the spectrum of the wave slope $S_{\alpha\alpha}$ is to be calculated as

$$S_{\alpha\alpha}\ w\ = \frac{\omega^4}{g^2} \cdot S_{zz}(w) \qquad (13)$$

This function could be estimated using a linear hydrodynamic software and has a global behavior similar to that of the non-dimensional roll moment. Long waves with low frequencies are fully effective, and for such waves the effective wave slope function is close to 1. Excitation due to short waves having high frequencies is almost negligible, and, thus $f_{r,waves}$ is close to zero. This allows to use a very simplified form for $f_{r,waves}(w)$: a step function that takes value 1 for frequencies lower than w_{lim}, and takes value 0 for values higher than w_{lim}, being w_{lim} the frequency corresponding to a wave having a length equal to one half of the ship breadth. While the ideal would be to associate each vessel its own effective wave slope coefficient, it must be underlined the fact that setting the wave slope equal to one is usually conservative, and has don herein only to provide a simplified approximate method for comparative purposes.

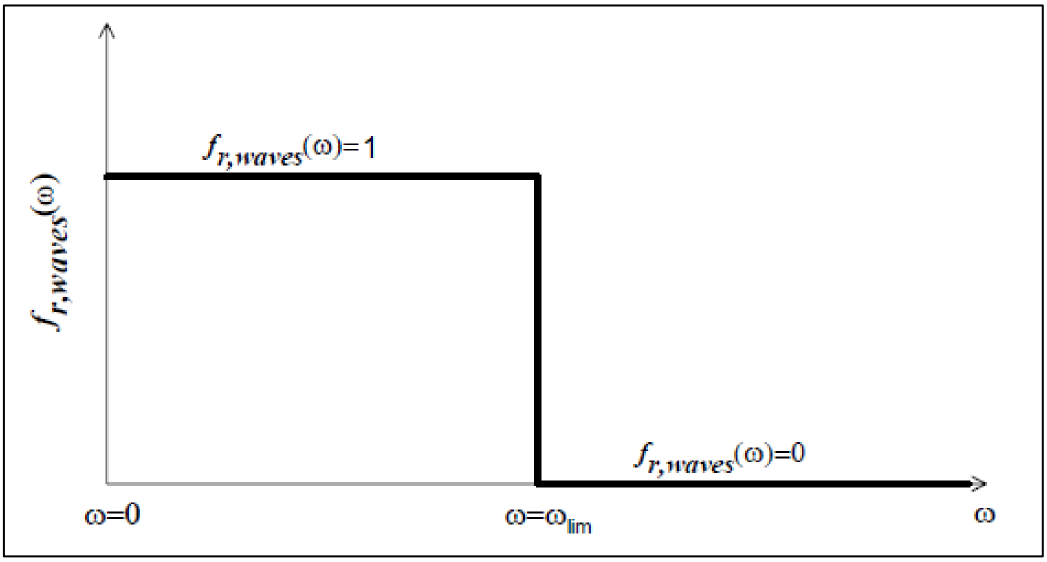


Figure 13. Simplified effective wave slope function

A graphical representation of this formula is shown in Figure 13, with

$$w_{lim} = \sqrt{\frac{2\pi \cdot g}{B \quad 2}} \tag{14}$$

where B is the ship breadth.

These two ways of obtaining the action of waves provide different results –as expected-. Both results are presented and the differences analyzed.

It is worth presenting the differences obtained in the roll moment by the two methods. Figure 14 shows the effective wave slope function calculated from the Froude-Krylov moments obtained by PRECAL for vessels F1 to P5.

These values are obtained for SSN4 (Hs=1.88 m, To= 8,8 s, Bretschneider wave spectrum) with heading 90º and 0 knots vessel speed.

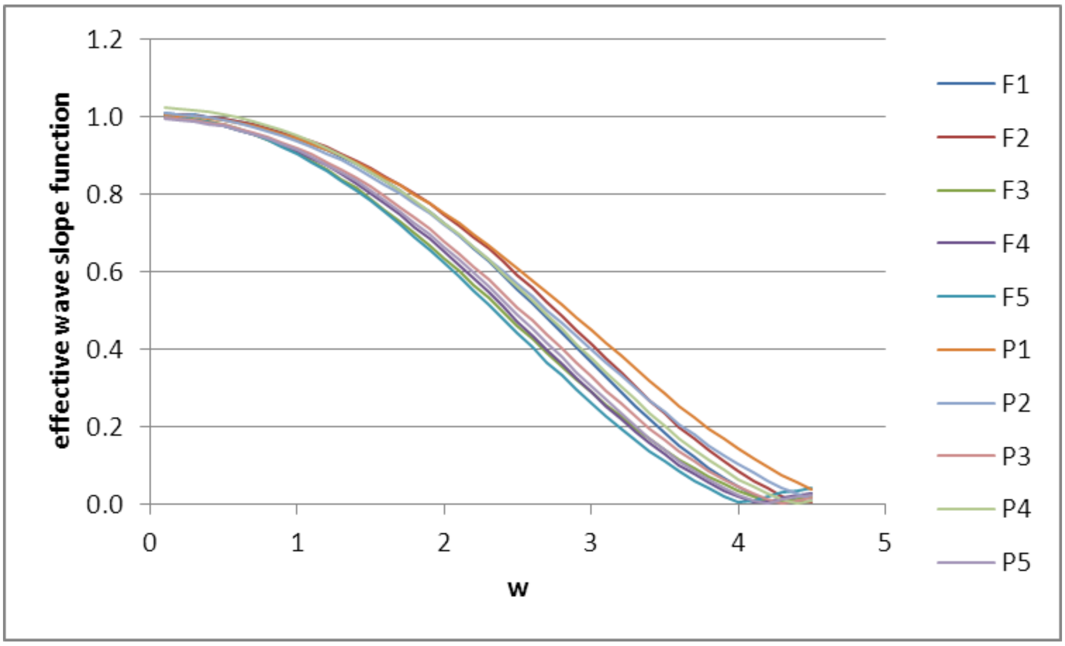


Figure 14. Effective wave slope function obtained from the Froude-Krylov roll moments calculated with PRECAL. Bretschneider wave spectrum with Hs=1.88 m, To= 8,8 s

Wind action

Wind action is modeled as explained by Bulian (Bulian and Francescutto, 2004). Wind speed field is modeled as a nonzero mean Gaussian process. When removing the mean wind V_w the gustiness can be characterized by a spectrum. The spectrum of the nondimensional fluctuating moment due to gustiness can be computed:

$$S_{\delta m_{wind}}(w) = \left(\frac{\rho_{air}.\overline{V}_w.C_y.A_L.\left(T + H_w - \overline{KG}\right)}{\Delta.\overline{GM}}\right)^2.S_{v,c}(w) \quad (15)$$

$$S_{v,c}(w) = \chi^2(w).S_{v(w)}$$

Where

- ρ_{air} is the air density
- V_w is the mean wind speed
- A_L is the lateral projected area
- Cy is the drag coefficient
- H_w is the distance from the waterline of the centre of aerodynamic pressures (positive upward)

- X(w) is the aerodynamic admittance function as proposed by Vickery (Vickery, 1968)

Water on deck

In this work the effect of water on deck has been also considered. This is a significant difference with respect to the methodology proposed by Bulian and Francescutto, and is an original contribution by the author.

The reason why considering water on deck is important is because it is usual in small fishing vessels to embark certain amount of water when hauling catches onboard. Some water drips from the wet net and catches, but also small fishing vessels that raise nets or lines at side, with reduced maneuvering capability and sometimes listed by the tension in the winches, are prone to get water embarked from the waves hitting the vessel`s side. Depending on the amount of water, this may become a dangerous situation which the vessel should be able to cope with. Stability criteria in rough weather should guarantee that the vessel has stability enough to withstand water on deck for a minimum time, necessary for the water to drain off or for taking the appropriate safety measures, such as cutting the net or maneuvering the vessel.

The relevant problem of estimating the effect of water on deck in small fishing vessels has been explored by some authors, being the works by Paroka and Umeda (Paroka and Umeda, 2007, 2006) similar in its approach to the methodology used. According to these authors, the effect of the water trapped on deck may be taken into account in the roll motion model as a net reduction of the GZ curve. They estimate the amount of trapped water on deck using a hydraulic flow assumption

Similarly, in this work the effect of water on deck has been estimated as a net reduction of the righting lever curve (GZ curve) caused by the static weight of a water wedge for each roll angle: Assuming that the deck is flooded with a given amount of water that extends uniformly along a fixed length, and considering a constant ship breadth and bulwark height for each vessel, the loss of GZ for each heeling angle is easily computable.

For convenience, a flooded length of 4 m for all vessels and a quantity of water equal to 3% of the vessel displacement in the studied loading condition has been chosen.

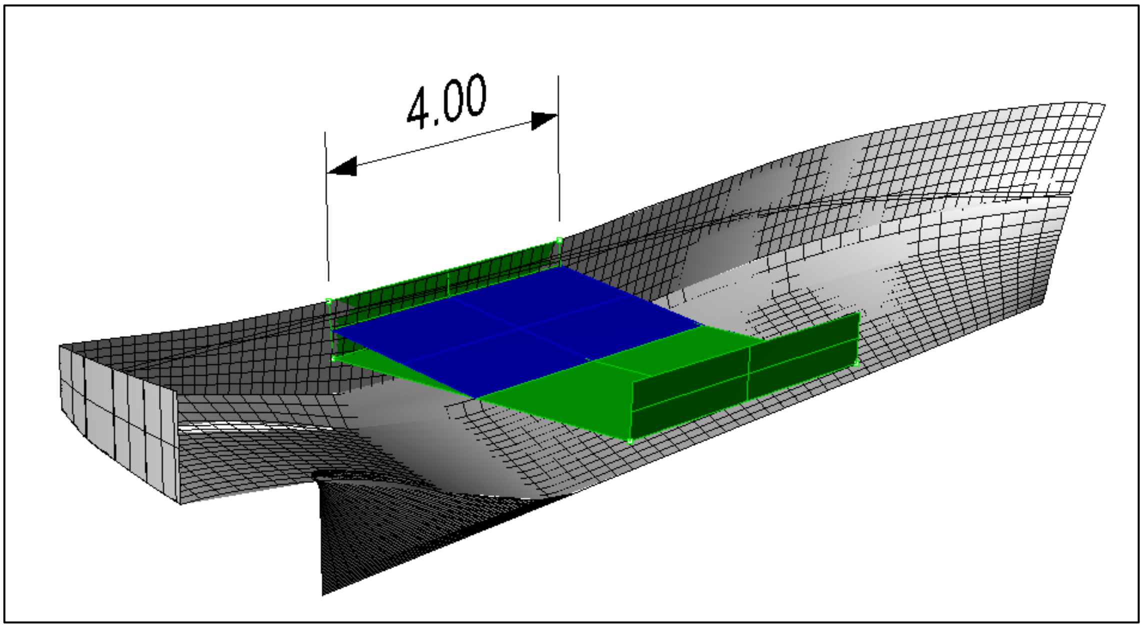


Figure 15. Water on deck over a 4 m long section of the vessel, to estimate GZ loss

For illustrating these calculations, Figure 15 represents the wedge of water considered, in blue color. In green it is represented the volume where the water on deck is located.

The loss of GZ for each heel angle given the amount of water embarked is easily computable and takes the form represented in Figure 16.

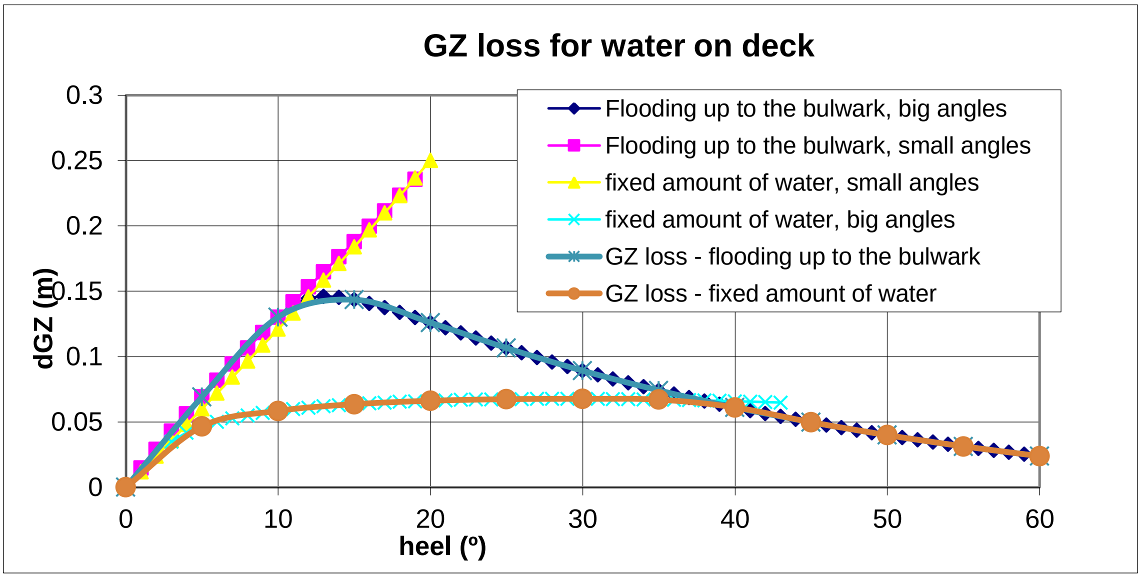


Figure 16. Typical curves showing the GZ loss due to shipment of water on deck, depending on the amount of water and heeling angle

This methodology has the obvious limitation of considering the effect of water on deck on the roll motion equal to the GZ loss for each static heel angle. This approach neglects the dynamic effects of the water motion on the vessel deck and, therefore, the results of the calculations with water on deck must be taken with caution.

Having this in mind, for the comparative purposes of this work, these calculations are believed to provide valid indicators of which vessels behave better with water on deck, as well as indicators of the performance deterioration in rough weather with water on deck.

Wind speed

Average wind speed V_w is correlated to significant wave height $H_{1/3}$ according to the following relation (IMO, 2009)

$$V_w = \left(\frac{H_{1/3}}{0.06717}\right)^{\frac{1}{1.5}} \quad (16)$$

Capsizing

The capsizing event is defined as the up-crossing of a certain "equivalent area virtual capsize" angle. In order to take into account the actual shape of the righting lever, two virtual capsize angles to leeward and windward are defined, in such a way that the area under the actual residual righting lever and under the linearized residual righting lever are the same. Such "equivalent area" virtual capsize angles are to be calculated as follows:

windward:

$$\varphi_{cap,EA-} = \varphi_s - \sqrt{\frac{-2}{GM_{res}(\varphi_s)} \cdot \int_{\varphi_{cap,-}}^{\varphi_s} GZ_{res}(\xi) d\xi}$$

leeward:

$$\varphi_{cap,EA+} = \varphi_s + \sqrt{\frac{-2}{GM_{res}(\varphi_s)} \cdot \int_{\varphi_s}^{\varphi_{cap,+}} GZ_{res}(\xi) d\xi} \quad (17)$$

Where $GZ_{\varphi} = GZ(\varphi) - l_{wind,tot}$ and $l_{wind,tot}$ is the heeling moment lever due to the action of the mean wind.

Roll spectrum

Assuming wind and waves moments to be Gaussian processes, locally uncorrelated, the spectrum of the total roll moment can be computed as the sum of the non-dimensional wind and waves moment spectra.

$$S_m(w) = S_{\delta m_{wind}}(w) + S_{m_{waves}}(w) \tag{18}$$

The final roll spectrum $S_x(\omega)$ can be obtained as follows:

$$S_x(w) = \frac{w_0^4 S_m(w)}{[w_e^2(\varphi_s) - w^2]^2 + [2 \cdot \mu \cdot w]^2} \tag{19}$$

Where φ_s is the static equilibrium heel angle under the action of the static wind with velocity V_w and ω_e is the modified roll natural frequency close to the equilibrium angle φ_s, given by the equation

$$w_e = w_0 \cdot \sqrt{\frac{GM_{res}(\varphi_s)}{GM}} \tag{20}$$

Where $GM_{res}(\varphi_s)$ is the derivative of the righting lever curve at φ_s.

The linear roll damping model chosen allows us to compute directly the spectrum as all terms in the right side of the above equation are known.

Capsize index and mean capsize time

From this point, the mean capsize time T_{cap} and the capsize index CI can be estimated. These magnitudes are given by the following expressions:

$$CI = 1 - \exp(-\lambda_{EA} \cdot T_{exp})$$
$$T_{cap} = 1/\lambda_{EA}$$
$$\lambda_{EA} = \frac{1}{T_{z,C_s}} \cdot \left[\exp\left(-\frac{1}{2 \cdot RI_{EA+}^2}\right) + \exp\left(-\frac{1}{2 \cdot RI_{EA-}^2}\right)\right] \tag{21}$$

$$RI_{EA+} = \frac{\sigma_{C_s}}{\Delta\varphi_{res,EA+}};\ \Delta\varphi_{res,EA+} = \varphi_{cap,EA+} - \varphi_s$$
$$RI_{EA-} = \frac{\sigma_{C_s}}{\Delta\varphi_{res,EA-}};\ \Delta\varphi_{res,EA-} = \varphi_s - \varphi_{cap,EA-} \tag{22}$$

The exposure time T_{exp} is taken equal to 3600 s, and the quantities σ_{Cs} and $T_{z,Cs}$ are to be determined:

$$\sigma_{C_s} = \sqrt{m_0}$$
$$T_{z,Cs} = 2 \cdot \pi \cdot \sqrt{\frac{m_0}{m_2}} \tag{23}$$

Where m_0 and m_2 are the variance of the roll and roll velocity, respectively. They are calculated as the spectral moment of order 0 and 2 of the roll spectrum.

Conditions of the analysis

For the ten vessels studied, T_{cap} and CI have been calculated with and without water on deck, in two sea states defined by the significant wave height and modal wave period according to the standardized scale adopted by NATO (Military Agency for Standarization, NATO, 1983). For all vessels, SSN4 and SSN5 have been studied, corresponding to significant wave heights of 1.88m and 3.25m with modal periods of 8.8s and 9.7 s respectively. The Bretschneider wave spectrum and exposure time of 1 hour have been considered.

6. RESULTS – ANALYSIS

6.1. Fishing fleet accident rate assessment

6.1.1. Loss rate in the Spanish Fishing Fleet

From the available data in SFFR and maritime accident data collected by CIAIM it is possible to estimate some statistical properties of the loss rate in the Spanish fishing fleet. They will be applied in our study, according to the methodology introduced in 5.2.

First, using MAGRAMA data referenced in section 1.4.2, a histogram of the number of lost flooded vessels by age is presented in Figure 17. The average is 25 years. An empirical cumulative distribution function (CDF) obtained from that histogram is shown in Figure 18. According to this CDF the sinking probability of a vessel under 9 years old can be estimated as 0.102. Even though age could be in principle considered a significant risk factor, it has not been explored to the candidate knowledge as a potential inequality factor in the literature.

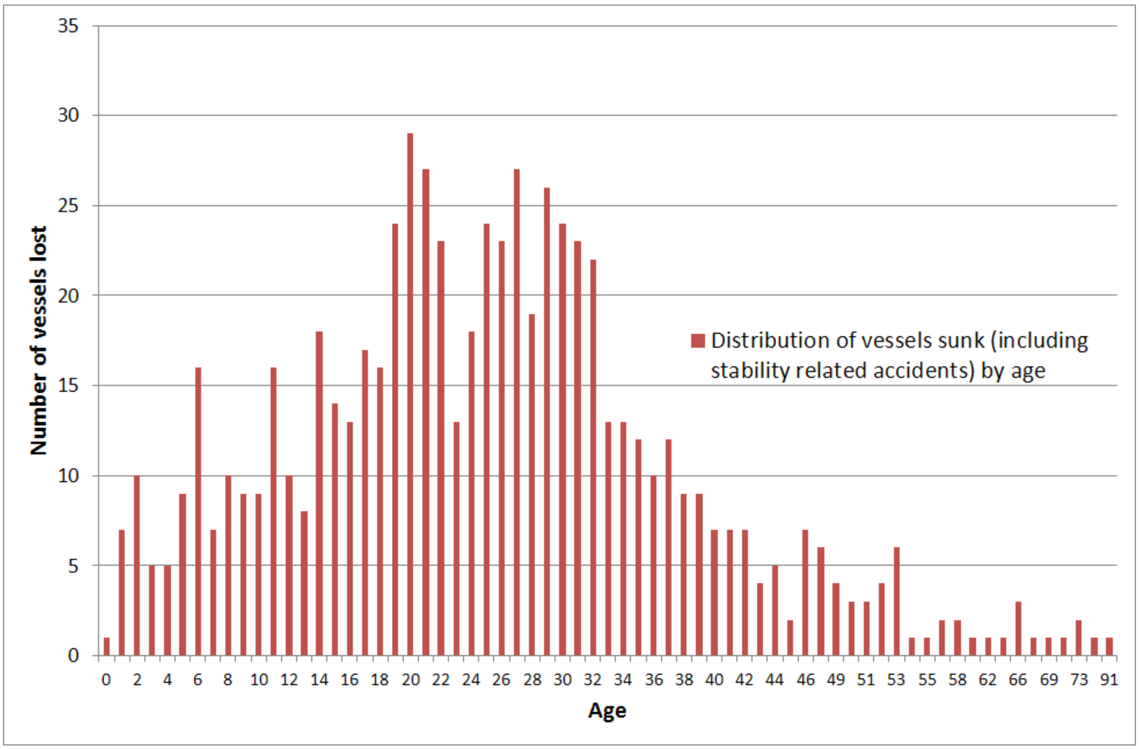


Figure 17. Sunk vessels distribution in Spain (Source: author, from MAGRAMA and CIAIM data)

Second, available CIAIM data, extracted from that referred to in section 1.5, allows to estimate as 4 occurrences per year the expected number of lost fishing vessels in Spain due to flooding.

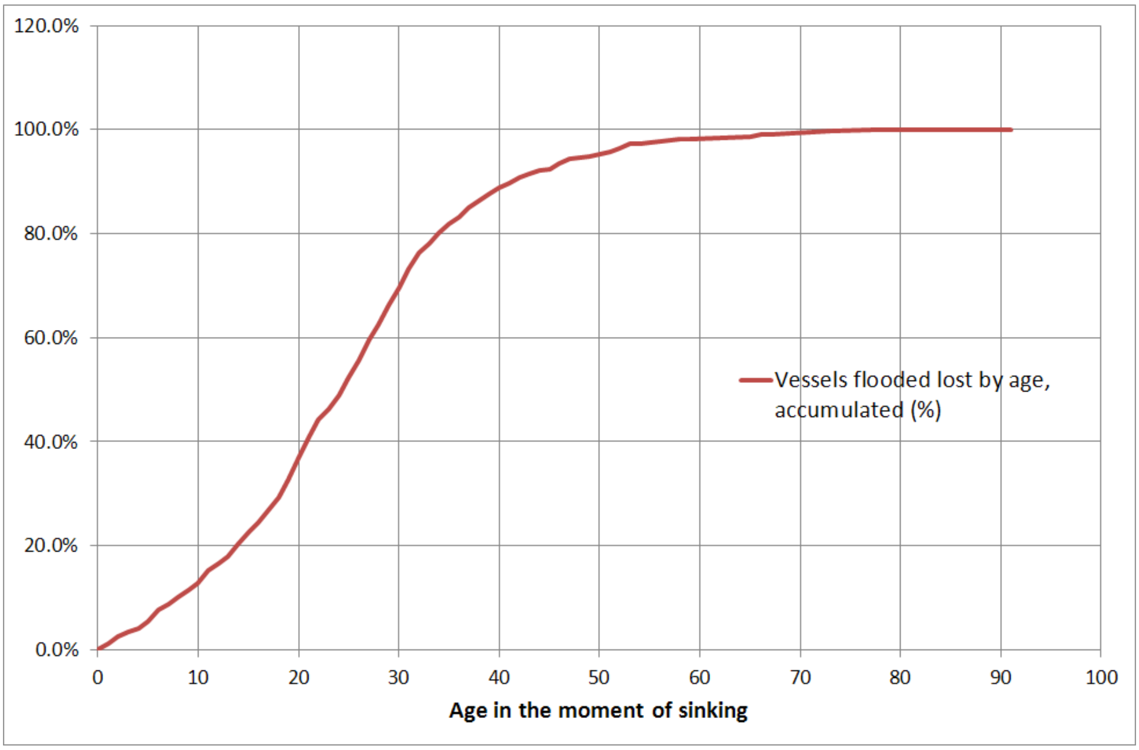


Figure 18. Cumulative distribution function of vessels sunk in Spain (Source: author, from MAGRAMA and CIAIM data)

6.1.2. Probabilistic assessment of the occurrence of the accidents

The case studies lengths are in the segment between 15 and 24 m and belong to the seines, liners and gillnets and entangling nets gear vessels categories (see Table 6 in chapter 4). According to the fleet distribution by length and fishing gear, the five vessels belong to a subgroup of the fleet that comprises only 6% of the Spanish fishing vessels. It should be noted that this same figure (6%) is obtained when the whole fleet of vessels registered since 1870 is considered, or when we look at the fleet of active vessels as of May 2013 (Table 3).

As discussed in previous section, the sinking probability of a vessel under 9 years old can be estimated as 0.102 (Fig. 15) and the expected number of lost flooded fishing vessels per year can be estimated as 4 (CIAIM data) . We therefore expect 12 losses in 3 years, in average, which is the period that includes the case studies. Assuming each of the 12 expected accidents as an independent random event, the number of losses under 9 years can be approximated by a binomial distribution with p=0.102 and n=12

(see e.g. Dekking et al., 2005). Under this assumption the probability of having 5 or more of these less than 9 years old vessels out of the expected 12 is around 0.005 (4.72e-3).

Also, see Table 6 , the case studies belong to a group of vessels that includes only 6% of the total amount of Spanish fishing vessels. Let's suppose first that the ship segments to which the vessels belong (the seines, liners and gillnets and entangling nets gear vessels categories) are not riskier than the rest of segments, and second that therefore we can roughly approximate the fact of a flooded vessel belonging to this group as a realization of a Bernouilli experiment with p=0.06. Under this assumption, the number of vessels of this kind within a series of 12 can be seen as a discrete binomial random variable. The probability of having 5 or more of those vessels out of 12 lost in 3 years is roughly 0.0005 (4.31e-4) (see e.g. Dekking et al., 2005).

To conclude, the probability that both conditions (age and vessel type) hold simultaneously is negligible, which indicates that the losses may not be independent and that therefore deserve a specific investigation.

6.2. Regulatory stability

6.2.1. General

The stability curves of the vessels studied are presented in Figure 19, where the stability curves of each vessel and her predecessor have been plotted together.

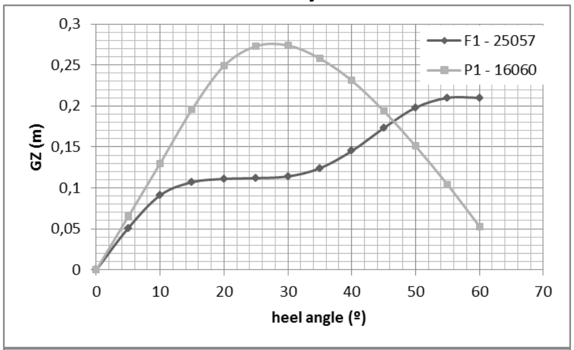
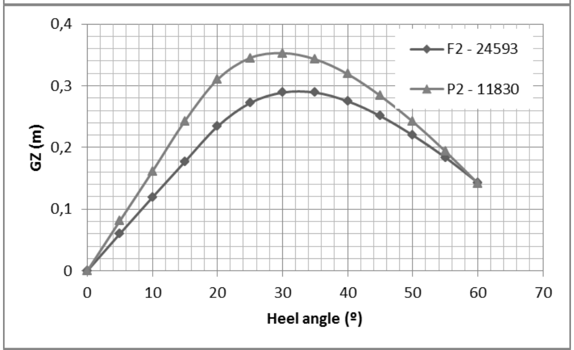
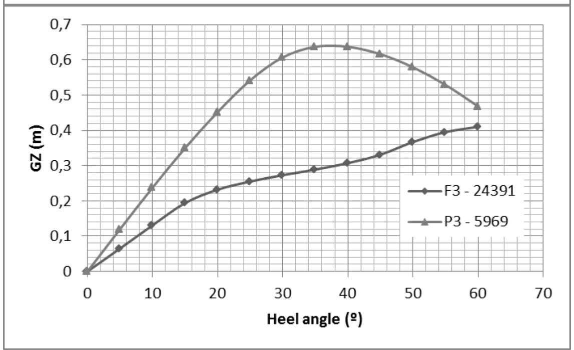
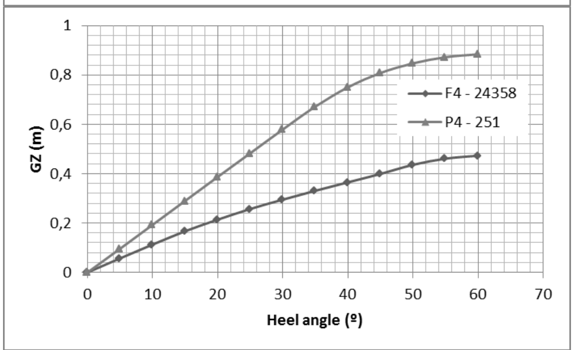
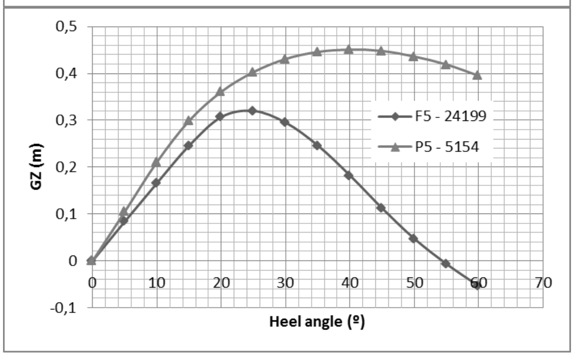
Vessels	Stability curves
Vessels F1-P1	
Vessels F2-P2	
Vessels F3-P3	
Vessels F4-P4	
Vessels F5-P5	

Figure 19. Comparison of stability curves of vessels (F1 to F5) and their predecessors (P1 to P5)

Table 16, summarizing stability calculations for all vessels, is presented below. As explained in the previous chapter, the stability index (SI) for comparison is the limiting KG margin, in percentage terms, over loading condition KG. The values of the stability index for the lost vessels (SI_F) and for the predecessors (Si_p), as well as the ratio between the two magnitudes, are included in Table 16.

Lost vessel	SI_F	Predecessor	SI_P	Ratio SI_P / SI_F
F1	2.7%	P1	11.0%	4.6
F2	9.9%	P2	19.7%	2.0
F3	6.7%	P3	51.0%	7.6
F4	10.1%	P4	8.0%	0.8
F5	2.0%	P5	37.0%	18.5

Table 16. Stability index (SI) of the lost vessels (F1 to F5) and their predecessors (P1 to P5)

6.2.2. Results analysis

It is remarkable that most predecessors present quite higher stability indexes than the newer vessels that substituted them. For the vessels F3-P3 or F5-P5 the differences are very noticeable. It is also remarkable that vessels F1 and F5, although complying with the criteria, had very little stability margin.

The differences in stability found are very noticeable in the case of purse seiners (F1, F3 and F5), having the old vessels quite more stability than the newer ones.

Regarding the stability curves calculated for each vessel, all predecessors had in general larger GZ in a wide range of heeling angles and, thus, dynamic stability, than the lost vessels. The lost fishing vessels had also lower GM than their respective predecessors.

6.3. Operability

6.3.1. General

In this section the results of the operability calculations are presented. Figure 20 to Figure 24 present operability graphics with areas where each criterion is exceeded for each vessel and predecessor and sea state. Safe zones (SZ in the graphics) where none criterion is exceeded are also displayed.

Superimposing the operability results for several criteria global operability maps for each vessel and sea state are obtained. Taking into account roll, pitch, vertical acceleration and lateral acceleration, such global operability maps for the five fishing vessels and their respective predecessors in SSN4 and SSN5 are shown in Figure 25 and Figure 26.

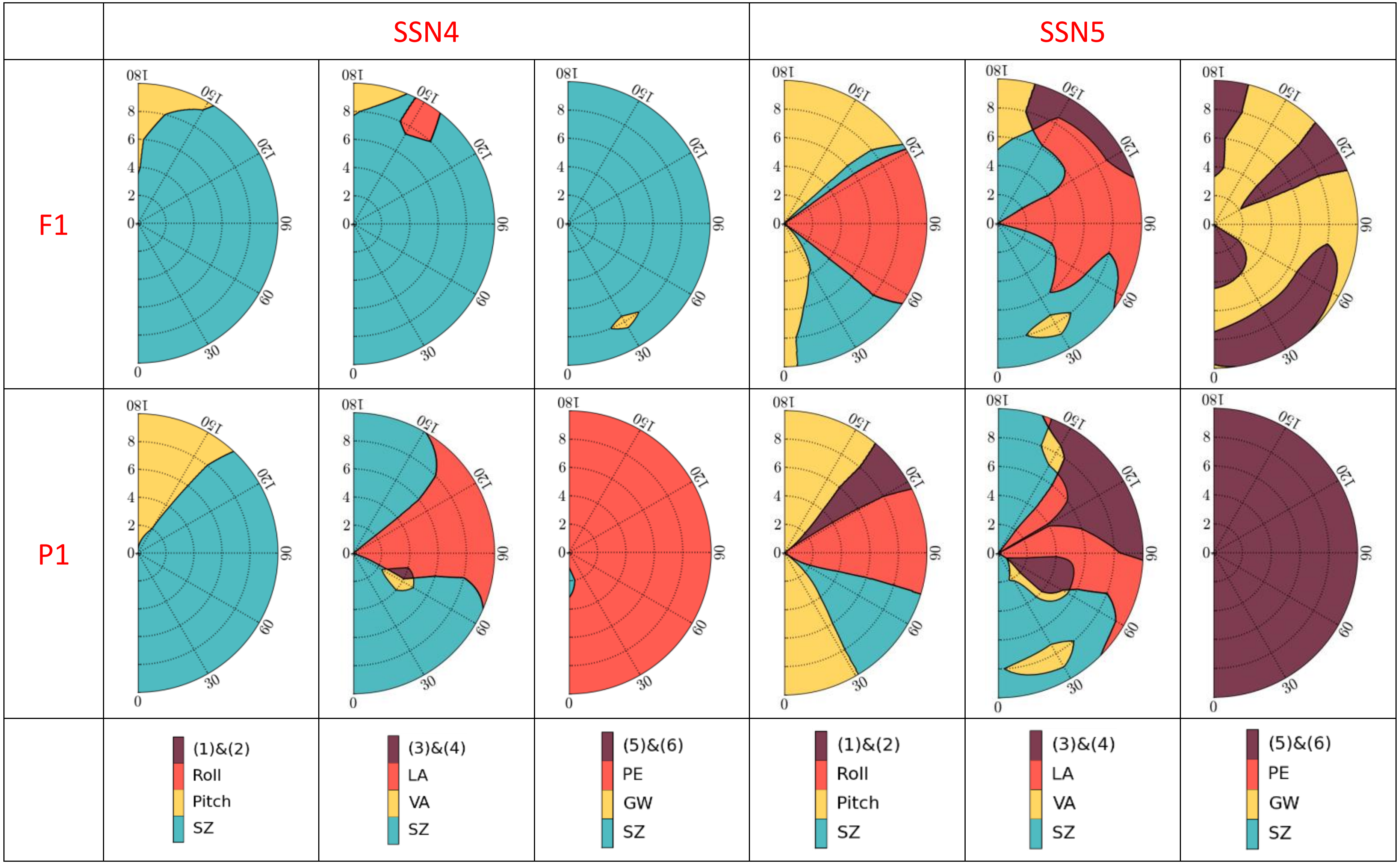


Figure 20. Operability of vessels F1 and P1, in SSN4 and SSN5

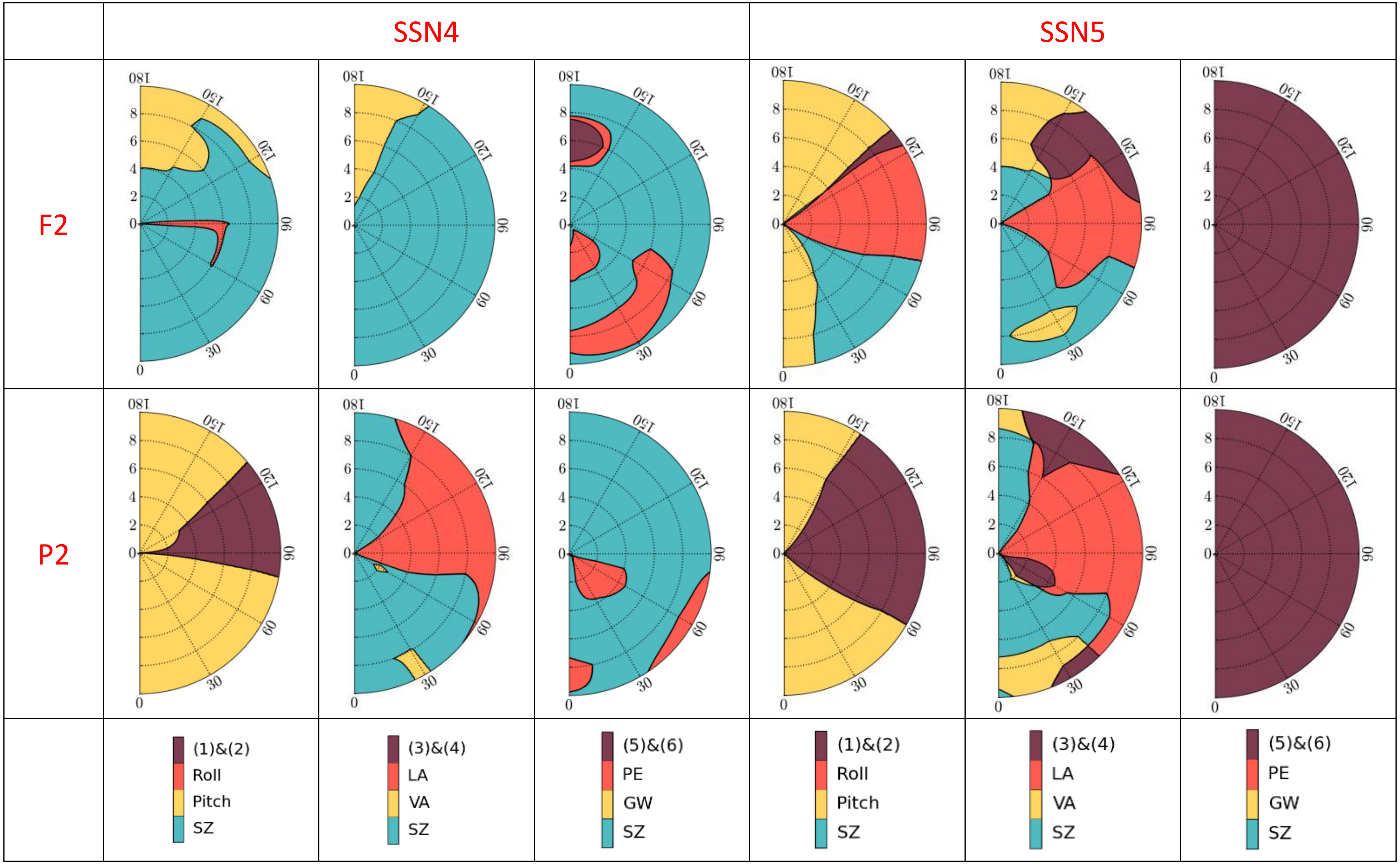


Figure 21. Operability of vessels F2 and P2, in SSN4 and SSN5

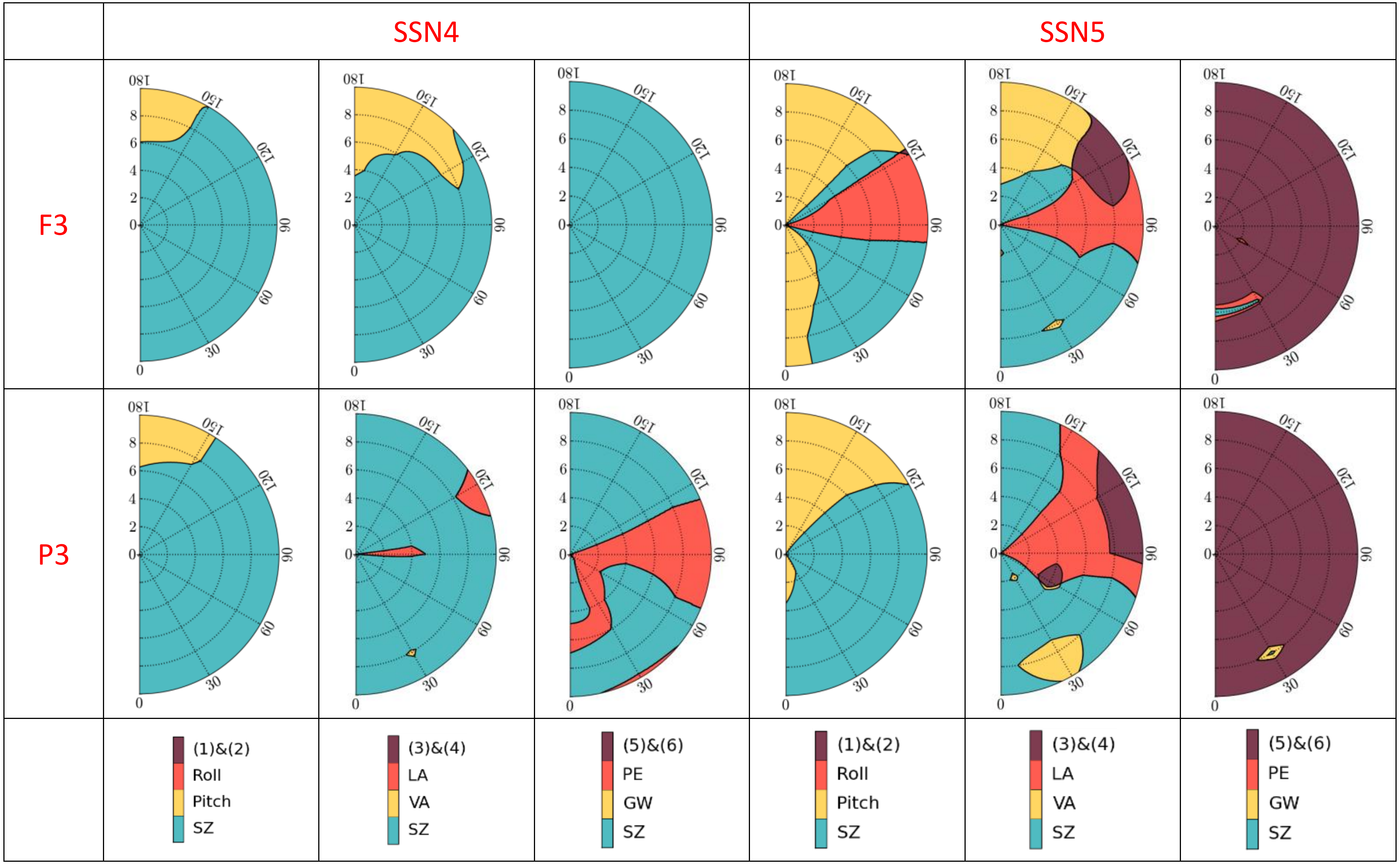


Figure 22. Operability of vessels F3 and P3, in SSN4 and SSN5

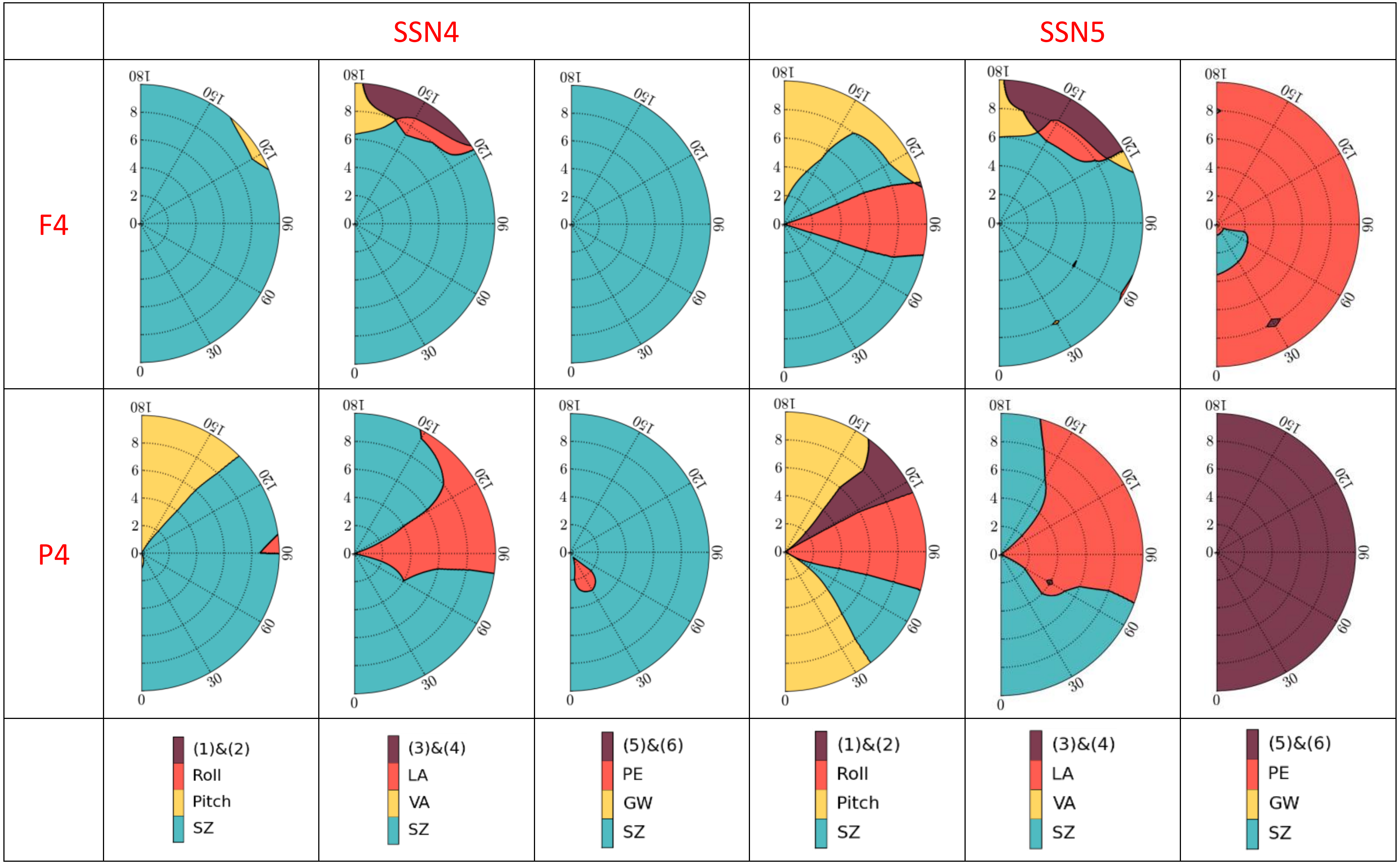


Figure 23. Operability of vessels F4 and P4, in SSN4 and SSN5

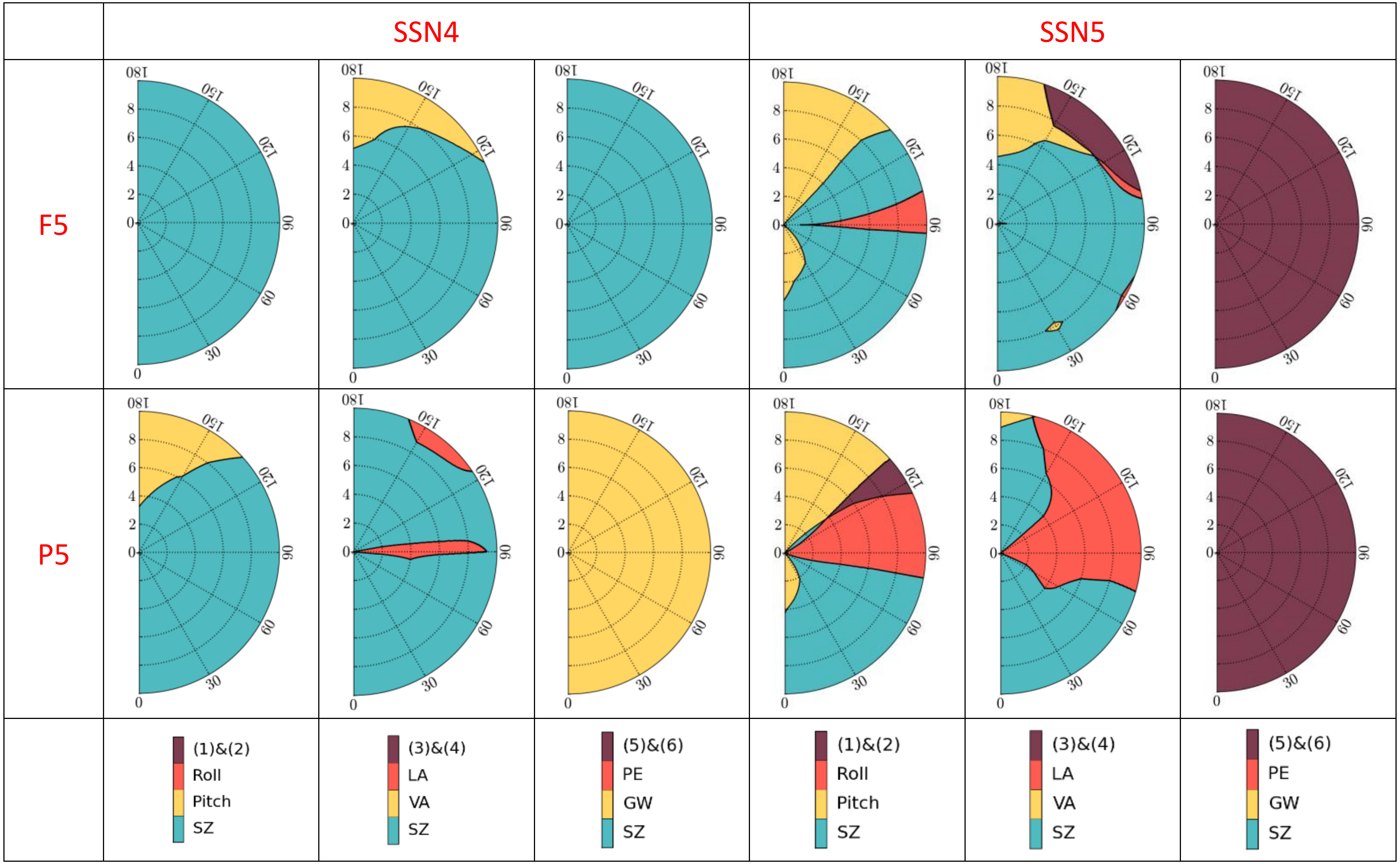


Figure 24. Operability of vessels F5 and P5, in SSN4 and SSN5

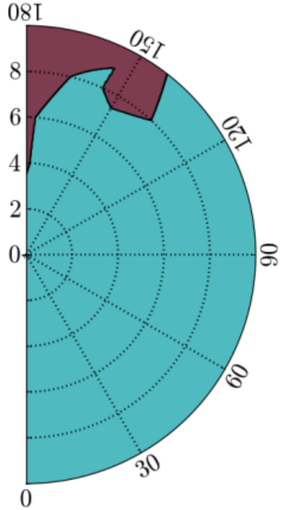
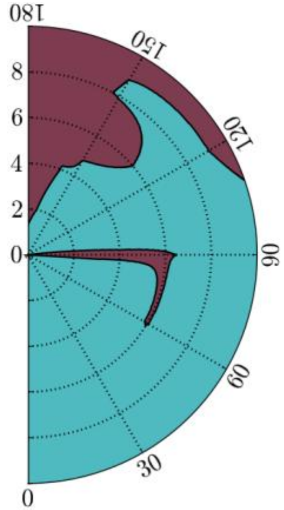
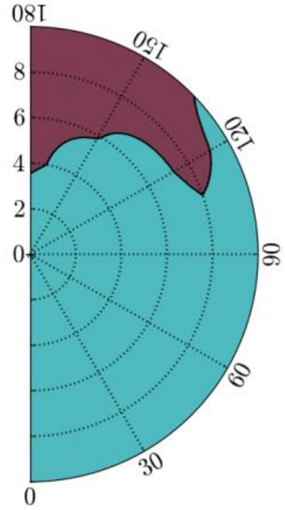
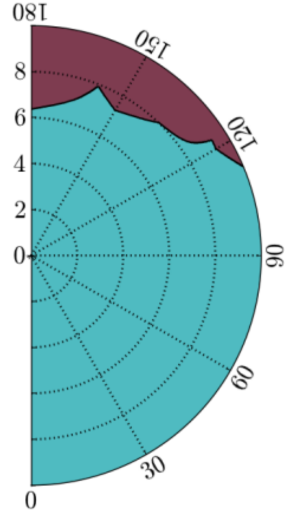
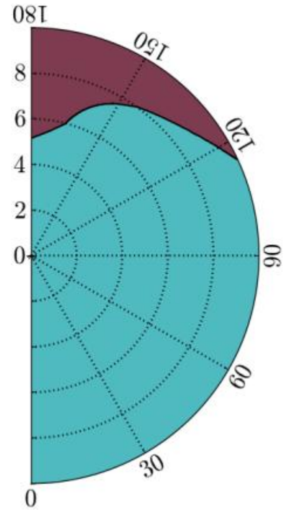
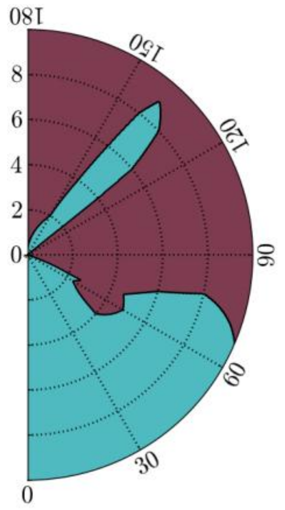
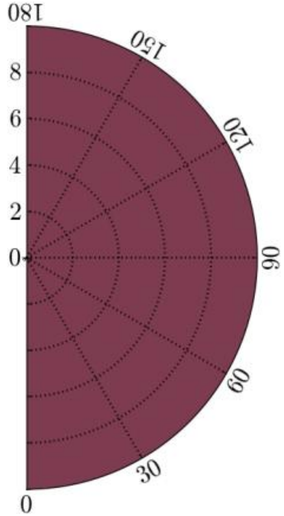
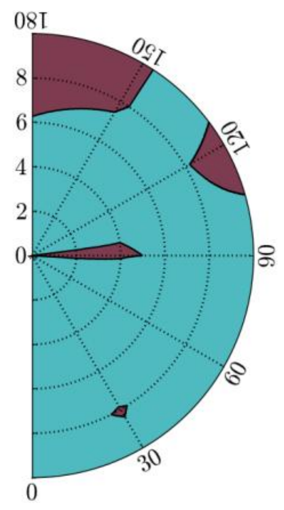
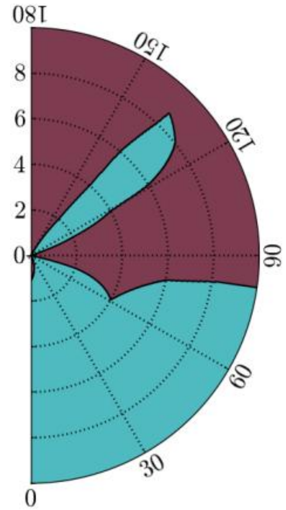
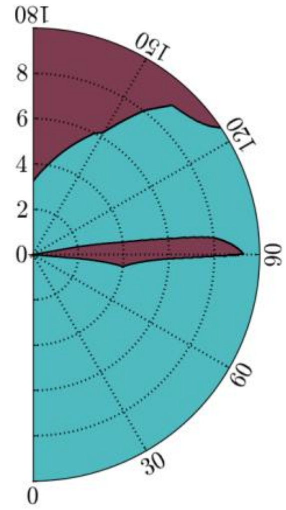
Operability in SSN4	F1 - P1	F2 - P2	F3 - P3	F4 - P4	F5 - P5
Vessel					
Predecessor					

Figure 25. Operability comparison of vessels F1 to F5 and P1 to P5, in SSN4, considering Roll, Pitch, Lateral Acceleration and Vertical Acceleration

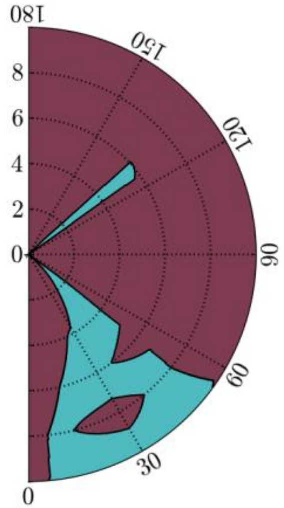
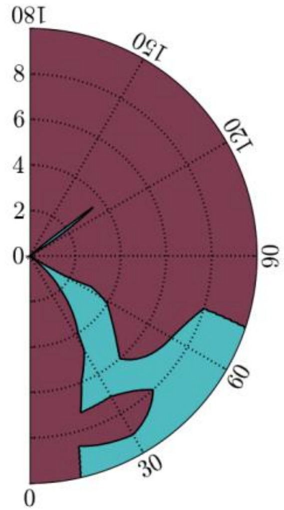
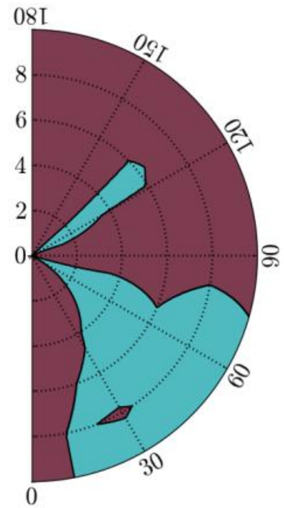
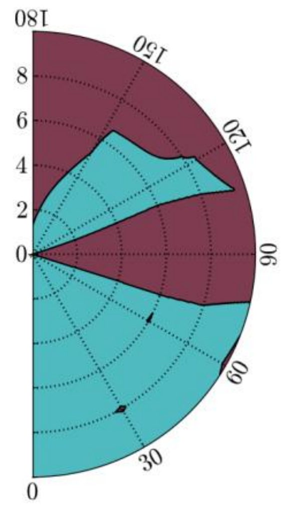
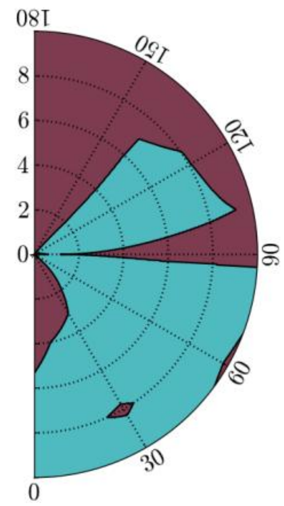
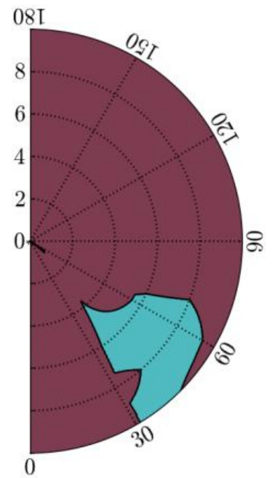
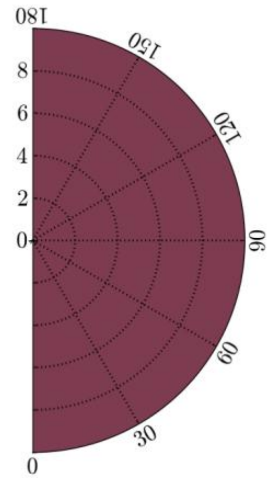
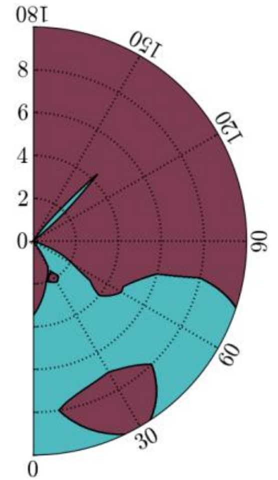
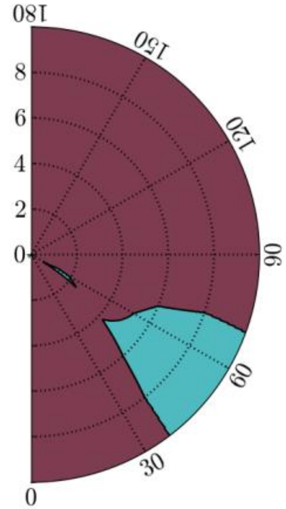
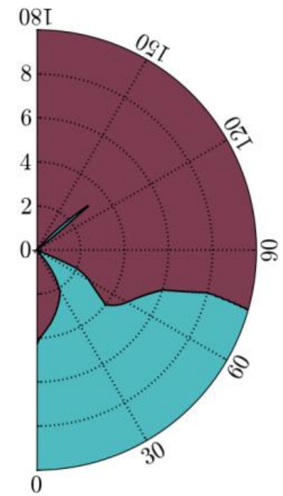
<table>
<tr><th>Operability in SSN5</th><th>F1 - P1</th><th>F2 - P2</th><th>F3 - P3</th><th>F4 - P4</th><th>F5 - P5</th></tr>
<tr><td>Vessel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td></tr>
<tr><td>Predec.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td></tr>
</table>

Figure 26. Operability comparison of vessels F1 to F5 and P1 to P5, in SSN5, considering Roll, Pitch, Lateral Acceleration and Vertical Acceleration

Table 17 summarizes the calculated operability index for all vessels, considering ship motions only, excluding episodic motions (green water and propeller emergence):

Operability Index in SSN4					
	F1-P1	F2-P2	F3-P3	F4-P4	F5-P5
Lost vessels (F1-F5)	0.94	0.81	0.86	0.92	0.91
Predecessors (P1-P5)	0.47	0.00	0.90	0.52	0.83
Ratio OI_P / OI_F	0.50	0.00	1.05	0.57	0.91
Operability Index in SSN5					
	F1-P1	F2-P2	F3-P3	F4-P4	F5-P5
Lost vessels (F1-F5)	0.17	0.15	0.30	0.62	0.59
Predecessors (P1-P5)	0.08	0.00	0.31	0.08	0.32
Ratio OI_P / OI_F	0.47	0.00	1.03	0.13	0.54

Table 17. Operability indexes of the lost vessels (F1 to F5) and their predecessors (P1 to P5)

6.3.2. Results analysis

Regarding the operability graphs and OI's calculated in the previous section, some conclusions can be drawn:

- Most of the lost vessels had greater operability than their predecessors. This difference is most noticeable in SSN4, where significant differences are found for F1, F2 and F4 with respect to P1, P2 and P4 respectively.
- For all vessels, operability deteriorates with increasing sea states. In SSN4 all lost vessels (F1 to F5) maintain high levels of operability, with the OI ranging between 0.81 and 0.96. The lost vessels operability deteriorates significantly in SSN5, except for F4 and F5, that still have OI of 0.62 and 0.59 respectively. Being these two vessels the largest ones amongst the ten studied, them having a larger operability is expected.
- Regarding the predecessors, more heterogeneity is found. Apart from P2, the OI of the other four vessels varies from 0.47 to 0.90. Regardless of the wave height being considered, excessive pitch responses above the limiting criterion have been found for the P2 case, which significantly reduces the global operability of the vessel. This might be attributable to this vessel

being the smallest one, with 11 m LOA, well below the rest of the studied vessels. Therefore, operability results for P2 must be cautiously taken.

When examining the operability results in Figure 20 to Figure 24, which present criteria separately, some points arise.

- In general, predecessors present lower operability than the lost vessels regarding the pitch motion criteria.
- Green water on deck and propeller emergence are quite sensitive to the sea state. Most vessels fulfill these criteria in any combination of heading and speed in SSN4 (Hs = 1.88 m) but fail to comply with them in SSN5 (Hs = 3.25 m) for most heading/speed combinations. Therefore, the operability of all vessels regarding this criterion drastically deteriorates with relatively small increases in wave height. For this reason, green water and propeller emergence are not useful criteria for comparative purposes between the two sets of vessels studied, since in all cases, the drastic operability deterioration occurs in a relatively small wave height interval.
- The most often exceeded criteria are pitch, roll, and lateral acceleration.
- Pitch becomes a problem for ship headings close to 180º (head seas) and high speeds. When increasing wave height, pitch in following waves (0º) also limits operability.
- In general, vessels P1 to P5 do not present larger roll motions than vessels F1 to F5. Roll is not a very limiting criterion in SSN4, except for vessel P2. Regardless of the speed of the vessel being considered and for headings around 90º (beam waves), roll criterion is a major limiting factor of operability of most of the vessels in SSN5. Notice this feature might pose a problem for vessels that operate at zero speed without maneuvering capability, especially, purse seiners while pulling the net and pulling catches onboard. A common scenario for those vessels, while pulling the net in bad weather, is to be pushed by wind and waves, ending transverse to the waves and suffering rolls that can put the vessel in danger (Mantari et al., 2011).
- Regarding vessel accelerations, some conclusions can also be drawn. Degradation of operability due to the lateral acceleration criterion being exceeded with increasing wave heights is significant for most vessels, while vertical acceleration criterion being exceeded is less dependent on sea state. Therefore, in general, lateral accelerations limit operability more than vertical ones. Lateral acceleration responses are significant for vessel

headings around 90º, which is a foreseeable result, being strongly correlated with the roll motion.

When looking at operability and taking into account all criteria simultaneously (Figure 25 and Figure 26), the following conclusions can be drawn:

- In general, operability of all vessels is more significantly impaired when facing bow waves (90-180º) for both sea states SSN4 and SSN5.
- In SSN5 vessels operability region gets confined to quartering seas (headings from 30º to 90º).

Comparing the stability characteristics of the ten vessels studied in section 6.2 with the operability results presented in section 6.3 some conclusions are reached.

- The lost vessels have, in general, larger operability but less stability than their predecessors.
- When comparing stability and operability between a lost vessel and her predecessor, large differences in operability not always imply large differences in stability. For instance, F4 and P4 have stability indexes quite similar (see Table 6) but the operability differences between F4 and P4 are quite significant (see Figs. 5, 7, 8). This suggests that there is no direct and obvious correlation between stability and operability.

Summarizing the previous results, it can be stated that operability studies based on linear seakeeping calculations may not be enough to assess ship safety. A consistent relation between ship stability and ship operability, calculated from linear seakeeping methods, has not been found. Due to the particular nature of the case studies (all vessels capsized in stability related accidents) the conclusion can be drawn that a direct link between operability and safety in the five cases studies and by extension for these types of vessels cannot be established.

6.4. Stability in rough weather

In this section the results of the stability calculations in rough weather are presented.

6.4.1. Weather Criterion

Table 18 presents the degree of compliance of the ten vessels studied with the Weather Criterion. Only two vessels (F1 and F2) fail to comply with the criterion, although it must be remarked, as anticipated in section 5.5.2, none of the case studies had to comply with Weather Criterion, as in all cases the area under the GZ curve up to 30º is larger than 0.065 m.rad.

Vessel	b / a (%)	Heel angle due to steady wind moment (deg)	Criterion compliance	Area under the stability curve up to heel 30º (A30)	Compulsory according to current stability regulations? (only if A30 < 0.065)
F1	15.1	9.8	Fails	0.066	No
F2	63.2	6.3	Fails	0.088	No
F3	143.1	7.1	Complies	0.088	No
F4	348.0	5.1	Complies	0.083	No
F5	125.6	5.9	Complies	0.12	No
P1	147.7	6.6	Complies	0.10	No
P2	193.4	5.9	Complies	0.116	No
P3	293.0	3.0	Complies	0.176	No
P4	306.9	3.4	Complies	0.152	No
P5	337.2	1.7	Complies	0.14	No

Table 18. Summary of the Weather Criterion results for the ten vessels studied

It is interesting that, while under the Spanish stability regulations in force, Weather Criterion was not required to be checked for F1 and F2, these two vessels failed to pass it.

It is to be noted a very low b/a ratio of about 15% for F1. When comparing the lost vessels with their predecessors, it can be seen that, in general, predecessors have more margin with respect to the criterion limits. Except F4, all the lost vessels have lower b/a ratio than any of the predecessors (Figure 27). Regarding the heel angle due to steady wind, in all cases predecessors have lower values, which is indicative of better stability (Figure 28).

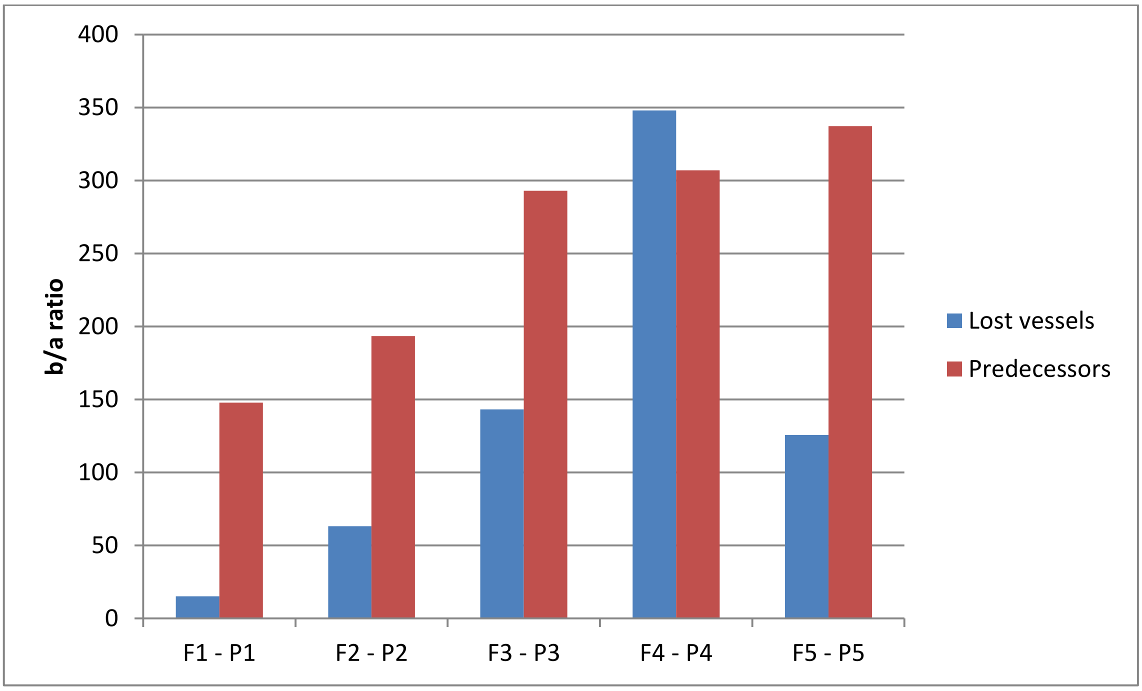


Figure 27. Weather Criterion. Ratio b/a comparison

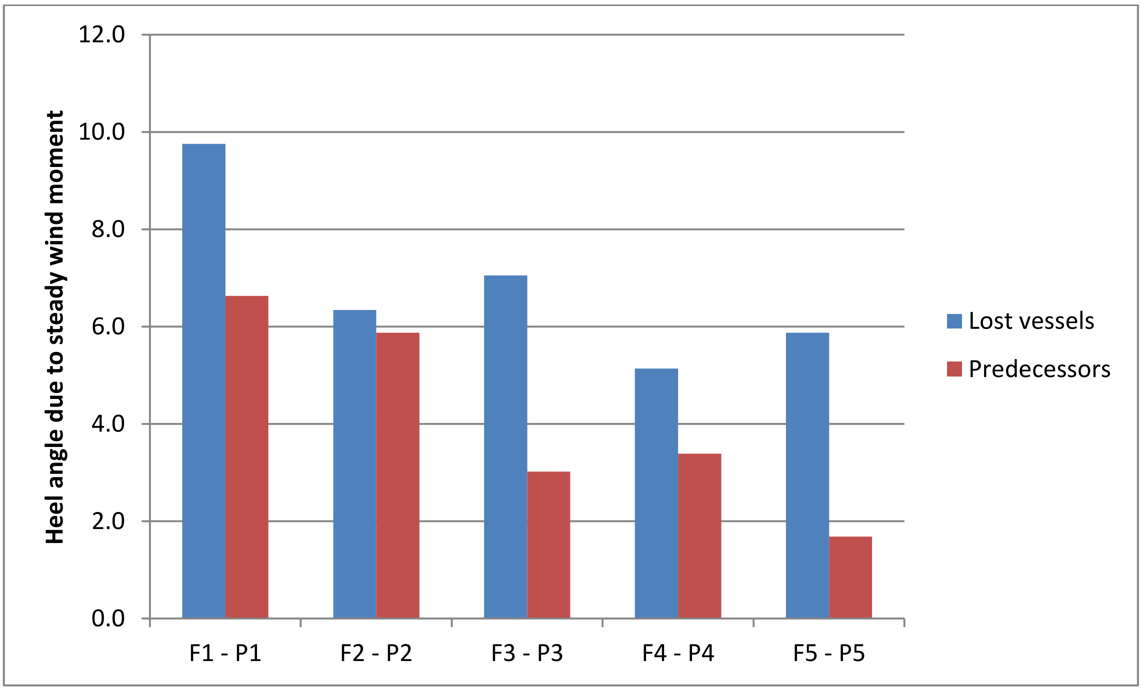


Figure 28. Weather Criterion. Heel angle due to steady wind moment comparison

6.4.2. Dead ship condition (2nd Generation Stability Criteria)

For the 10 vessels studied, Capsize Index (CI) and Mean Capsize Time (T_{cap}) have been obtained according to the methodology explained in section 5.5 for a combination of the following situations:

- Sea states: SSN4 and SSN5.
- Water on deck: without water on deck, and considering an amount of water on deck equal to 3% of each vessel displacement.
- Roll moment: calculated with linear seakeeping software and calculated with a simplified effective wave slope function.

Table 19 to Table 22 summarize the results of the performed calculations.

SSN4 – roll moment computed with linear seakeeping software PRECAL							
Vessel	Without water on deck			Water on deck = 3% disf			
	Static heel angle (º)	CI	Tcap (hours)	Water on deck (m3)	Static heel angle (º)	CI	Tcap (hours)
F1	0.8	5.33E-04	1875	2.084	4.7	0.001418	704.55
F2	0.6	3.958E-07	2526427	1.56	2.1	3.904E-05	25613
F3	0.7	8.068E-08	1.239E+8	2.36	2.2	2.129E-06	469612
F4	0.5	8,114E-12	1,232E+11	2.863	1.9	3.500E-09	285732681
F5	0.6	5.433E-05	18407	2.596	1.7	0.002163	461.97
P1	0.8	0.0041365	241.2	0.732	2.4	0.3885	2.033
P2	0.6	1.585E-05	63087	0.634	1.6	0.020714	47.774
P3	0.3	8.056E-09	1.241E+8	1.276	0.6	7.365E-05	13576.6
P4	0.4	5.601E-10	1.785E+09	1.44	0.7	1.749E-06	571641
P5	0.2	1.46E-07	6847793	1.994	0.3	0.000311	3210.37

Table 19. Dead ship condition. Capsize Indexes (CI) and mean capsize time (Tcap) in SSN4. Roll moment computed with linear seakeeping software PRECAL

SSN5 – roll moment computed with linear seakeeping software PRECAL							
Vessel	Without water on deck			Water on deck = 3% disf			
	Static heel angle (º)	CI	Tcap (hours)	Water on deck (m3)	Static heel angle (º)	CI	Tcap (hours)
F1	1.7	0.898827	0.44	2.084	8.1	1.0000	0.07
F2	1.3	0.060066	16.14	1.56	4.1	0.7537	0.71
F3	1.5	0.034321	28.63	2.36	4.3	0.4718	1.57
F4	1.1	0.000404	2477.51	2.863	3.7	0.0409	23.98
F5	1.3	0.498709	1.45	2.596	3.4	0.9995	0.13
P1	1.6	0.986700	0.23	0.732	4.5	1.0000	0.03
P2	1.2	0.271029	3.16	0.634	3.2	0.9997	0.12
P3	0.6	0.008210	121.30	1.276	1.2	0.4461	1.69
P4	0.7	0.002221	449.67	1.44	1.4	0.1006	9.43
P5	0.4	0.030468	32.32	1.994	0.7	0.7162	0.79

Table 20. Dead ship condition. Capsize Indexes (CI) and mean capsize time (Tcap) in SSN5. Roll moment computed with linear seakeeping software PRECAL

SSN4 – roll moment computed with simplified effective wave slope function							
Vessel	Without water on deck			Water on deck = 3% disf			
	Static heel angle (º)	CI	Tcap (hours)	Water on deck (m3)	Static heel angle (º)	CI	Tcap (hours)
F1	0.8	0.012652	78.5	2.084	4.7	0.00853	116.70
F2	0.6	0.000141	7105.5	1.56	2.1	0.00066	1515.39
F3	0.7	0.000098	10170.0	2.36	2.2	8.27E-05	12098.6
F4	0.5	0.000002	464736.8	2.863	1.9	1.68E-06	596493.7
F5	0.6	0.011733	84.7	2.596	1.7	0.03155	31.19
P1	0.8	0.075432	12.8	0.732	2.4	0.56350	1.21
P2	0.6	0.007261	137.2	0.634	1.6	0.10886	8.68
P3	0.3	0.001136	879.9	1.276	0.6	0.01244	79.86
P4	0.4	0.000049	20328.1	1.44	0.7	0.00020	4940.86
P5	0.2	0.019307	51.3	1.994	0.3	0.08040	11.93

Table 21. Dead ship condition. Capsize Indexes (CI) and mean capsize time (Tcap) in SSN4. Roll moment computed with simplified effective wave slope function

SSN5 – roll moment computed with simplified effective wave slope function							
Vessel	Without water on deck			Water on deck = 3% disf			
	Static heel angle (º)	CI	Tcap (hours)	Water on deck (m3)	Static heel angle (º)	CI	Tcap (hours)
F1	1.7	1	0.119	2.084	8.1	1	0.042
F2	1.3	0.5790	1.155	1.56	4.1	0.9900	0.217
F3	1.5	0.5464	1.265	2.36	4.3	0.9380	0.360
F4	1.1	0.1099	8.586	2.863	3.7	0.4049	1.926
F5	1.3	0.9992	0.140	2.596	3.4	1	0.046
P1	1.6	1	0.060	0.732	4.5	1	0.018
P2	1.2	0.9949	0.189	0.634	3.2	1	0.048
P3	0.6	0.8766	0.478	1.276	1.2	0.9988	0.148
P4	0.7	0.3702	2.163	1.44	1.4	0.6433	0.970
P5	0.4	0.9997	0.125	1.994	0.7	1	0.060

Table 22. Dead ship condition. Capsize Indexes (CI) and mean capsize time (Tcap) in SSN5. Roll moment computed with simplified effective wave slope function

In order to have a clearer view about which vessels have better stability in dead ship condition, a comparison of results obtained for the case studies and their predecessor is summarized in Table 23. In the five right columns for each vessel and predecessor it is stated which vessel present lower CI (and hence better stability) for every calculation performed. When both vessels have a CI equal to 1 they both appear in the table.

Analysis condition			F1-P1	F2-P2	F3-P3	F4-P4	F5-P5
SSN4	Roll moment PRECAL	No water on deck	F1	F2	P3	F4	P5
		Water on deck	F1	F2	F3	F4	P5
	Roll moment effective wave slope	No water on deck	F1	F2	F3	F4	F5
		Water on deck	F1	F2	F3	F4	F5
SSN5	Roll moment PRECAL	No water on deck	F1	F2	P3	F4	P5
		Water on deck	F1-P1	F2	P3	F4	P5
	Roll moment effective wave slope	No water on deck	F1-P1	F2	F3	F4	F5
		Water on deck	F1-P1	F2	F3	F4	F5-P5

Table 23. Dead ship condition. Vessel with lower Capsize Index between each vessel and her predecessor for every calculation performed is presented.

These results are presented graphically in Figure 29 to Figure 33, where the analysis condition represented in the abscissa axis is defined in Table 24.

Analysis condition number	Sea State	Wave moment	Water on deck
1	4	PRECAL	No
2	4	PRECAL	Yes
3	4	Simpl. Wave slope function	No
4	4	Simpl. Wave slope function	Yes
5	5	PRECAL	No
6	5	PRECAL	Yes
7	5	Simpl. Wave slope function	No
8	5	Simpl. Wave slope function	Yes

Table 24. Definition of analysis conditions

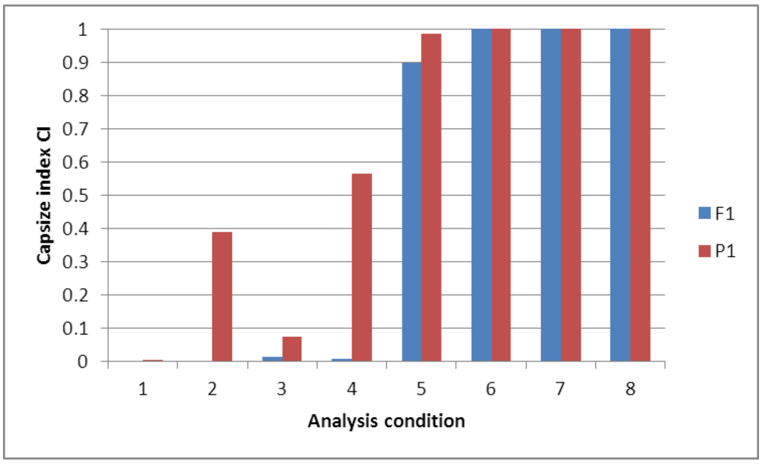


Figure 29. Short term Capsize Index for vessels F1 and P1

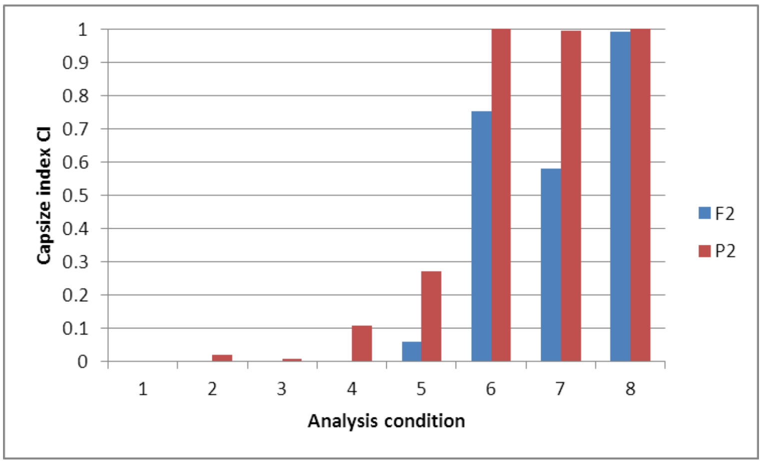


Figure 30. Short term Capsize Index for vessels F2 and P2

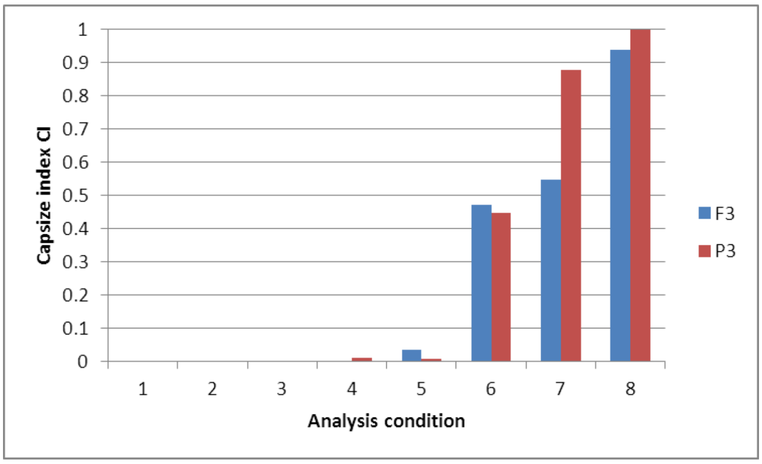


Figure 31. Short term Capsize Index for vessels F3 and P3

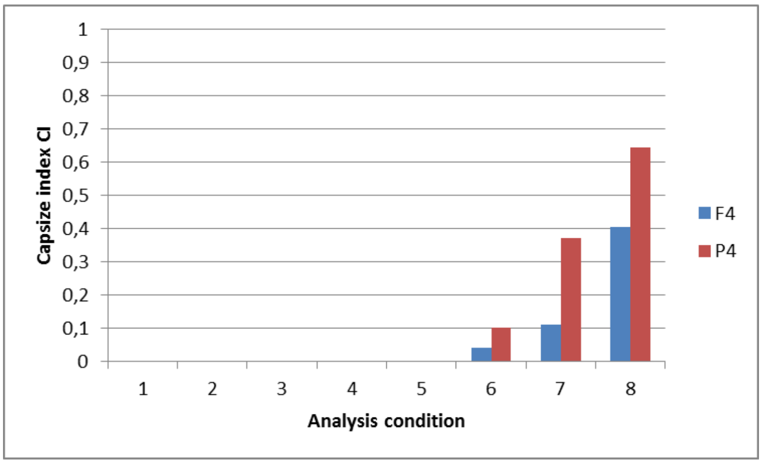


Figure 32. Short term Capsize Index for vessels F4 and P4

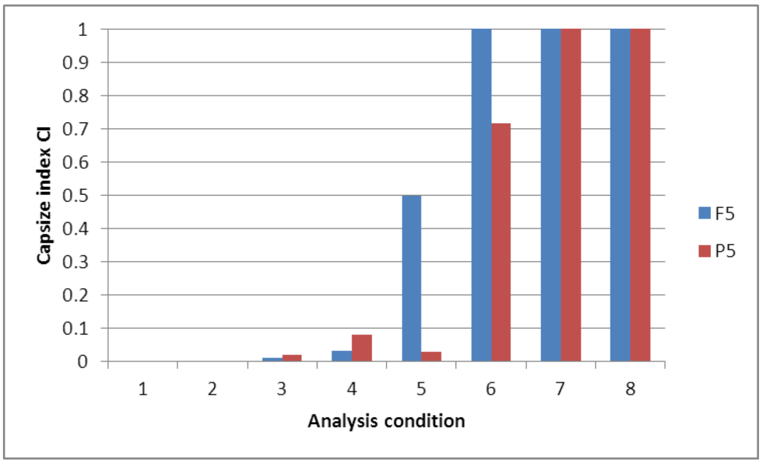


Figure 33. Short term Capsize Index for vessels F5 and P5

6.4.3. Results analysis

The main result of the analysis is that in general predecessors present worst stability regarding SGISC dead ship condition, except for the pair F3-P3 and F5-P5, for which the trend is not so clear.

One outcome observed looking at Table 19 to Table 23 and Figure 29 to Figure 33 is that in general higher CI's are obtained when using the simplified effective wave slope function for estimating the wave moments than the CIs obtained using the PRECAL Froude-Krylov roll moments. This is an expectable result, as in general the simplified effective wave slope function reaches higher values in the frequency calculation domain than the effective wave slope estimated by the seakeeping program (see Figure 13 and Figure 14).

A second interesting result is the deterioration of the capsize indexes and capsize times when considering water on deck in SSN4, regardless the method used for roll moment computation. This deterioration becomes a serious safety concern in SSN5, being Tcap for all vessels around a few hours.

The comparisons between F3-P3 and F5-P5 provide different results depending on which roll moment calculation method is chosen. For instance, comparing vessels F3 and P3 in SSN5, if roll moment is obtained by PRECAL calculations, P3 results to have lower CI (that is to say, better stability performance). On the contrary, if the wave roll moment is estimated by the simplified effective wave slope, F3 results with better stability. This suggests that in some cases the simplified effective wave slope may not provide the needed accuracy at estimating wave roll moment for the intended regulatory use.

Except for the pairs of vessels F3-P3 and F5-P5, in general, the lost vessels seem to have better behavior in dead ship condition than the predecessors.

According to the results obtained, it seems the two methods used for comparing the stability in rough weather (IMO standard Weather Criterion, and 2nd Generation Stability Criteria dead ship condition) does not correlate. While according to Weather Criterion predecessors show in general better performance, in dead ship condition the lost vessels tend to have smaller capsize indexes.

6.5. Joint Results analysis

6.5.1. General

The results obtained in the stability and operability analyses can be summarized in a table which compares the performance of each lost vessel with her predecessor in the four analyses performed, see Table 25.

Vessels	Stability curves and Stability index (SI): compares stability performance regarding the stability criteria that were in force when all vessels were built. See sections 5.3 and 6.2	Operability and Operability Index (OI): compares the level of motions experienced on board. See sections 5.4 and 6.3	Stability in rough weather – Weather Criterion: Compares the fulfillment of the Weather Criterion, even though it was not mandatory when the vessels were built. See sections 5.5 and 6.4	Stability in rough weather – SGISC dead ship condition: Compares the vessels performance regarding the stability criteria proposed to IMO for the dead ship condition in the framework of the 2nd generation stability criteria. See sections 5.5 and 6.4
F1 vs P1	P1 presents significantly higher SI than F1 (11% vs 2.7%)	F1 has a OI significantly higher than P1 in sea states 4 and 5.	P1 has sufficient b/a ratio. F1 fails to comply with the criterion (b/a < 100%)	P1 capsize index is larger than F1, regardless the roll moment computation method, presence of water on deck, in SSN4.
F2 vs P2	P2 presents significantly higher SI than F2 (19.7% vs 9.9%)	P2 has no operability in both sea states. OI of F1 passes from 0.81 in SSN4 to 0.15 in SSN5	P2 has sufficient b/a ratio. F2 fails to comply with the criterion.	In general P2 presents better stability.
F3 vs P3	P3 presents much higher SI than F3 (51% vs 6.7%)	Both vessels present OI values quite similar in both sea states	P3 has twice as b/a ratio as F3, while both vessels comply sufficiently with the criterion.	Depending on the roll moment calculation method, P3 or F3 result with better stability
F4 vs P4	P4 presents a bit lower SI than F4 (8% vs 10.1%)	F4 has higher operability than P4 in SSN4, while P4 stills has a substantial operability (OI=0.52). In SSN5 P4 operability drastically degrades, while F4 stills maintains a good operability (OI=0.62)	The margin of compliance of F4 is a bit higher than P4's (348% vs 306%). Both vessels comply comfortably with the criterion.	F4 presents better performance than P1 in general.
F5 vs P5	P5 presents much higher SI than F5 (37% vs 2.0%)	Both vessels have similar operability in SS4, but P5 operability degrades more than F5 in SSN5.	P5 complies loosely with the criterion, while F5 has a small margin over the minimum b/a required (125%)	Depending on the roll moment calculation method, P5 or F5 result with better stability

Vessels	**Stability curves and Stability index (SI): compares stability performance regarding the stability criteria that were in force when all vessels were built. See sections 5.3 and 6.2**	**Operability and Operability Index (OI): compares the level of motions experienced on board. See sections 5.4 and 6.3**	**Stability in rough weather – Weather Criterion: Compares the fulfillment of the Weather Criterion, even though it was not mandatory when the vessels were built. See sections 5.5 and 6.4**	**Stability in rough weather – SGISC dead ship condition: Compares the vessels performance regarding the stability criteria proposed to IMO for the dead ship condition in the framework of the 2nd generation stability criteria. See sections 5.5 and 6.4**
Comments	In general predecessors had substantially more regulatory stability margin than the lost vessels. SI of the lost vessels rages from 2.0% to 10.1%, while varies from 8% to 51% in the predecessors.	Four of five lost vessels have much higher Operability Indexes than the respective predecessors. Operability of predecessors degrades more in SSN5, having only two of the five vessels capability to operate.	Four of the five lost vessels present worst behavior regarding this criterion than their respective predecessors.	Three of the predecessors present worst behavior in dead ship condition than the lost fishing vessels.

Table 25. Joint stability and operability results analysis

6.5.2. Additional remarks

Some additional issues are worth presenting:

1. The stability curves for vessels F1 and F3, presented in Figure 19, have a peculiar behavior. These curves grow regularly between 0 and 10-20 degrees, then, the curves remain almost horizontal up to 30-40 degrees, and finally the growing ratio increases again. The reason is that the main deck is submerged because of a reduced freeboard, then, the stability increases again when the watertight superstructures are submerged as heel increases.

2. According to the operability results, in SSN5, for most speeds studied, ships tend to be more operative in headings of 30-60º (following waves). It is interesting to realize that navigating with these headings may impose additional risks, due to the dynamics of vessels in stern seas, not contemplated in the operability studies. It is well documented (IMO, 2007) that for those headings and speeds, fishing vessels may be at risk of surf-riding and broaching. In addition, with respect to Table 6, it is stated that some of the vessels studied which sunk could have experimented surf-riding and broaching. In addition, seakeeping calculations in following waves can have inherent issues due to the fact that the response amplitude operators (RAOs) of surge, sway and way motions tend to diverge at zero encounter frequency.

3. According to the authors' professional experience, it is not uncommon that fishing vessel masters identify stability with a low level of motions on board. A vessel with high operability may generate false safety perceptions on the crew, and the master in particular. Small amplitude ship motions, reduced pitch / roll / accelerations may be perceived by the masters as a symptom of good stability, while according to the findings of this work it is not necessarily true, that is to say, there is no strong relation between stability and operability. That suggests that fishing vessel safety cannot be assessed neglecting the human element, only by the study of ship motions or ship stability. This reinforces the idea that more investigation about ship motions on a seaway is needed. The relationship between ship stability, safety and motions must be investigated. These conclusions also suggest that an adequate training in stability for fishing vessels masters is needed.

4. Four comparison methods (statutory stability criteria, operability, Weather Criterion and dead ship condition) have been used to assess the safety differences between each vessel and her predecessor. Two of these methods (statutory stability criteria and Weather Criterion) are strongly based on the characteristics of the GZ curve, specially the areas below the

curve; which is a synonym of energy. Implicitly or explicitly in these two methods an energy balance is involved. The other two methods (operability and dead ship condition) are based on the vessel motions dynamics; that is to say, try to describe the motion of a vessel subject to a given set of forces and torques. It is to be noted that according to the first two methods mentioned (statutory stability criteria and Weather Criteria) predecessors show better stability than the lost vessels. Simultaneously, the motion-based methods (operability and dead ship condition) show the opposite behavior. It may be reasonably argued that the two first methods mentioned represent better the reality observed. A possible explanation for this could be the excessively simple roll damping model used in these analyses.

7. CONCLUSIONS

7.1. General

A series of five fishing vessel stability related accidents happened in Spain between 2004 and 2007 have been analyzed in the present thesis. The vessels lost had been built after the entry into force of a new fishing effort control regulation in Spain which imposed design requirements on new building which did not exist previously. Five vessels built in the same time frame, which sunk due to stability related causes in a short period of time.

The first aim of the thesis has been establishing the statistical relevance of the five accidents studied. From that, the following main objectives have been pursued:

- Studying the influence of the fishing effort control regulation on ship stability.
- Discussing the aptitude of operability analysis by means of linear seakeeping to assess the stability of fishing vessels.
- Discussing the suitability of some specific rough weather stability criteria to assess fishing vessel stability.

To achieve these objectives the lost vessels have been compared with the fishing vessels which were decommissioned to build them, referred to as "predecessors", according to the vessel replacement scheme imposed by that regulation. These predecessor vessels, which ended up their service life in a regular way, are considered as a safety reference. It is relevant to stress that the shipowners, masters and crews of the capsized vessels were the same ones that had been operating the predecessors, in the same fishing areas, using the same fishing gear type, and in the same social framework. The comparison is extended to the following areas:

- Regulatory stability.
- Operability, obtained by means of linear seakeeping studies.
- Stability in rough weather. Two methods are studied for assessing stability in rough weather: the IMO Weather Criterion, and the 2nd generation stability criteria in dead ship condition, under development by IMO.

7.2. Accident rate in the Spanish fishing fleet

Evidence has been given that the set of five accidents under study constitute a statistical anomaly. Considering only the ship sizes and fishing gears, the probability of five such vessels sinking in the given time interval is negligible.

The common characteristic among the five lost vessels was that they had been built shortly after the entry into force of the Royal Decree 2287/1998.

This suggests a relation worth investigating between that fishing effort control regulation and the aforementioned set of accidents.

7.3. Fishing effort

Fishing effort control policies based on tonnage limitations put in place in Spain in the years 1998-2009 have been discussed in this work. Evidences have been presented indicating that a series of stability loss related accidents with fatal consequences that took place between 2004 and 2007 are a statistical anomaly worth studying. This series of accidents share some common characteristics that suggest a relationship between them and the approval of the Spanish RD 2287/1998, regulating the fishing effort. Such regulation allowed, in practical terms, for the increase of enclosed spaces above the main deck in new vessels aiming at improving the health and safety and working conditions of fishermen.

It has been shown that due to this regulation, the lost vessels presented a set of ratios between their principal dimensions and stability parameters significantly different from those of the vessels built before the entry into force of the 1998 rules. All these differences point in the direction of a reduction of the ship stability margins.

Summarizing, the facts discussed in this work suggest that the 1998 fishing effort control related tonnage limitations may have had a negative effect over the stability of some kinds of fishing vessels with dramatic consequences.

Regulators and policy-makers should bear in mind that safety is a transversal aspect to all regulations affecting ship design, and that a strong maritime safety assessment should be performed during the approval process of any maritime regulation.

7.4. Stability and operability

In this work, the intact stability and short term operability of ten small fishing vessels have been studied.

The intact stability of each vessel has been characterized by her stability curve in a characteristic loading condition, and by a stability index, defined as the rate of the KG margin over the limiting KG that allows the ship to fulfill the IMO intact stability criteria with respect to the actual loading condition KG. The Weather Criterion has not been considered in this point of the analysis since it was not applicable to the selected vessels when these were designed and built.

The stability of each lost fishing vessel has been compared with the stability of her predecessor. It has been found that the new vessels had in general lower stability than the predecessors. Notwithstanding that, the ten vessels fulfilled the IMO stability criteria and hence, from the stability point of view, they could be considered equally safe.

Considering the similar context in which capsized vessels and predecessors were operated, this stability analysis opens a question mark on the suitability of intact stability criteria for these cases and therefore the possibility of analyzing the vessels operability in order to characterize the vessels safety has been explored. The masters operate the ships responding to the fulfillment of operability criteria and interrupt fishing operations only when those are surpassed and operation is no longer possible. They are hence the first to assume that a ship with a larger operability range is a safer ship.

Operability of each vessel has been established by calculating her short-term motions in two typical sea states with linear seakeeping analysis, and checking these motions against a set of operability criteria. A global operability index has been defined for comparison purpose. The operability of each pair of vessels (sunken vessel and predecessor) has been compared, resulting in the capsized vessels having more operability than the predecessors.

As a main conclusion, the comparison between the stability characteristics of two sets of vessels and the comparison between the operability characteristics of the same two sets of vessels throw opposite results. While the predecessors had in general more stability, the lost ones had in general larger operability. Thus the masters of the new fishing vessels could have considered them to be safer, as they experienced, in general, lower motions and accelerations, while in fact the new vessels were less stable than their predecessors, and might had required a more careful operation.

Overall, these results indicate that usual operability criteria may not contribute much to assess ship safety during design phases. It also suggests that masters should be strongly trained in stability, making them able to adequately manage their vessel's stability regardless of the operability behavior.

As a final remark, taking again into account that the sunken vessels fulfilled IMO stability criteria and had larger operability than the predecessors, the author believes

that more effort is needed towards developing and validating new, more complex stability criteria, able to capture the reality of the dynamics of fishing vessels at sea.

7.5. Stability in rough weather – Weather criterion and SGISC

Motivated by the conducted intact stability and operability analysis, a study of rough weather performance has been conducted. It comprises the analyses of the fulfillment of IMO Weather Criterion and of Second Generation Intact Stability Criterion (SGISC) in dead ship condition, yet under development.

The analysis conducted has not thrown consistent results in regards to pointing to the lost vessels as less secure from the point of view of these rough weather criteria.

Considering the variability in the results obtained, it is guessed that further validation work might be needed for ensuring that Second generation intact stability criteria (SGISC) in dead ship condition is providing a robust methodology to quantitatively determine capsizing probabilities for regulatory purposes. The large sensibility of short term capsize index CI and capsize time Tcap formulation to small input parameters variations may indicate that further validation is needed in order to ensure the methodology it suitable for early design stability assessment or regulatory purposes, as in design stages many vessel parameters are still uncertain or may have a large variability which would affect the values of CI and Tcap.

At this stage, this methodology is believed to provide good guidance at design stages when comparing different design options or comparing vessels.

Small fishing vessels are strongly sensible to water on deck. The large stability reduction in the form of CI increments or TCap reductions, even with small amounts of water on deck, clearly shows it. Being the probability of getting water on deck directly related to freeboard, this sensitivity reinforces previous conclusions regarding the influence of the fishing control effort regulation on ship safety, as this regulation has been demonstrated to have influenced design in the sense of reducing freeboard in general, for keeping gross tonnage below deck constant.

7.6. Future work

During the development of this thesis some research and future work opportunities have arisen, being the most relevant the following ones:

- It is advisable to review the accident rates in the fishing sector as new data are available. That can give place to identify new relations between accident rates and regulatory changes or other factors.

- It is worth studying the performance of the fishing vessels studied under the rest of failure modes contemplated in the IMO 2nd generation stability criteria, when these are quasi-definitively established.

- More sophisticated methods for calculating vessel motions, namely, a multi degrees-of-freedom time-domain non-linear numerical model able to calculate wave and wind induced ship motions and hydrodynamic loads in a realistic seaway would allow catching complex phenomena and establishing vessels operability more precisely.

- Using a more sophisticated roll damping model in operability studies and in dead ship condition studies could allow obtaining more refined conclusions regarding the comparison among the studied vessels.

- More complex water on deck models which can couple with vessel motion models are needed to assess the dynamics of a fishing vessel with water on deck.

7.7. Final remarks: a reflection on ship safety and stability

This work has presented strong indications that a regulatory change that occurred in Spain may have had negative consequences on the security of a segment of the fishing fleet built thereafter.

This allows to propose a reflection on the evolution of the designs of ships from the point of view of safety and the validity of the mechanisms to ensure the safety of the designs (stability criteria in this case, e.g. similarly fire protection measures, etc.)

Conceptually, it can be stated that the ship design is largely conditioned:

- by the requirements due to the economic activity carried out the vessel (transport of goods, fishing, port services, etc...), and

- by the regulations governing the activity.

In the case of fishing, the type of fishing gear, campaign or species to which the activity is directed clearly conditions design. For example in case that fishing is directed to specific high value low volume catches in nearby waters, small and fast vessels with limited fishing holds are expected to be efficient, to arrive early to the fishing grounds and return early to the fish market. Due to this, it is found that most ships destined for a given activity, a certain port and built in nearby years, are very similar. For example, considering fishing trawlers at the Gran Sol fishing grounds, North Sea supply vessels, or container feeders operating in a certain range of distance, the set of more efficient ships in any of these sectors share many characteristics.

Balancing this demand or commercial pressure that drives designs, the regulatory framework limits the design options, with the aim of guaranteeing the safety of the crew, the ship and her cargo, as well as other goods - in the broad sense - that should be protected (avoid damage to third parties or contamination of the environment, sustainability of fishing grounds, etc.)

The design of vessels, therefore, is conditioned by the balance of these two "forces" acting in opposite directions. As a result of the adaptation to small changes in these major design drivers, ship designs evolve slowly over time, towards a new point of balance that provides ships which conform better to the new conditions; that is, more efficient vessels within the regulatory framework. Therefore, every new generation of ships is not expected to be very different from the previous, whatever the type of vessel or exploitation, provided that there are not abrupt changes in the two aforementioned factors.

In this scenario, therefore, levels of risk in a particular sector of the fleet (whatever the way this level is measured) would be expected to remain within a strip of variability below a certain acceptable risk threshold.

In the author's opinion, the level of risk can remain under a certain threshold, provided that the changes in these factors are relatively slow. In the event of sudden changes in any of these two factors, the imbalance could make that the level of risk temporarily exceeds the acceptable threshold (Figure 34).

We could think, for example, in the introduction of a new disruptive[5] technology that allows higher ship operation efficiency; quickly designs will adopt this new technology. If this technology involves negative safety effects not accounted for in the existing regulations, the accident rate of the fleet could increase until the situation is balanced via policy changes. However, in the absence of sudden changes, the evolution of designs governed by the adaptation to economic activity conditions and policy changes can be done without exceeding the acceptable risk threshold.

[5] For instance, introduction of ro-ro vessels.

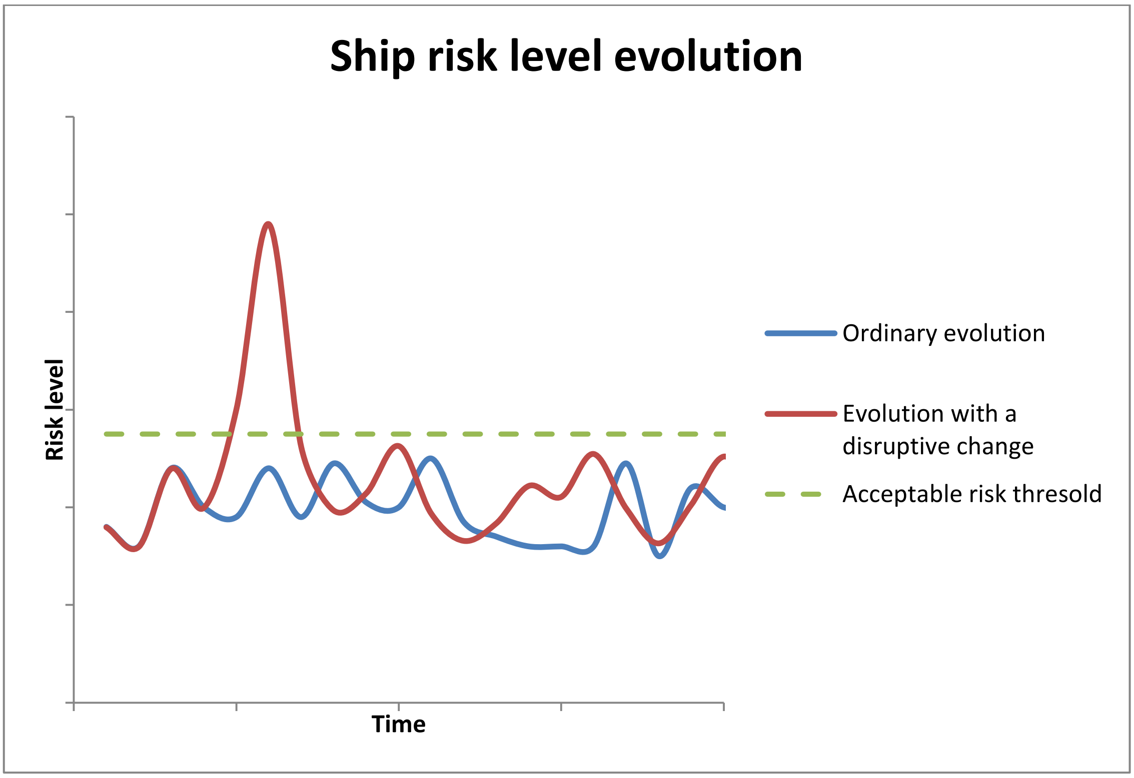


Figure 34. Ship risk level evolution

Similarly, a change in the rules governing the activity can have severe implications on ship safety, which existing regulations are not in a position to deal with. In the author's opinion, the accident rate increase shown in this study is an example of this: a sudden change occurs in the mode of operation of vessels by changes in the fishing effort regulations with implications on the stability that existing regulations cannot adequately manage.

There are practical examples that confirm this. The sinking of the fishing vessel FURACAN in the estuary of Muros and Noia (*Investigación del hundimiento del pesquero FURACAN y fallecimiento de uno de sus tripulantes cerca del puerto de Portosín (A Coruña) el día 29 de agosto de 2009*, n.d.) was influenced by the modification, by the regional government of Galicia, of the rules governing fishing gears, allowing the sunk ship to carry more pots on board than initially approved. The impact on the safety of vessels affected was not evaluated. It was assumed that the existing stability rules would satisfactorily cope with the stability reduction produced by the new gear, without assessing whether the fishing vessel safety had diminished, due to its usual operation below acceptable standards.

Accepting the previous approach, a corollary arises: the safety criteria are relative, adjusted to a mode of exploitation of each type of ship. There are no criteria that guarantee the safety of all vessels under all conditions. A sudden change in the

conditions of exploitation of the ships or their typology can cause safety criteria to be insufficient or ineffective. Accepting this paradigm, it is concluded that, before any modification of the regulatory framework or any adaptation of vessels to new conditions of exploitation, it is necessary to evaluate carefully these conditions from the safety point of view, and being prepared to react appropriately to the negative effects that may arise.

Focusing on transverse stability of small fishing vessels, the current stability standards, based on the characteristics of the righting arm curve, has somewhat generalist and comprehensive scope, as it can be seen from its origin and evolution. IMO is currently developing the establishment of performance based stability criteria to replace or complement (it is not yet clear) the current standard, based on the performance of the ships in a set of failure modes.

This initiative is commendable and necessary, as experience has shown that the existing stability standards are limited and do not respond adequately to certain requirements of the reality of the operation of the vessels. However, the current approach of the IMO has two drawbacks:

- First, the situations which a vessel must face possibly escape from the ability to forecast of the promoters of this approach; although a ship may successfully respond to the different failure modes studied, and
- Second, any reference to the human element and the possibility of human error is neglected. In a similar way as the dynamic behavior of the vessel is studied, the influence of human action on the stability of the vessel, whereas faulty or intentional actions (inappropriate headings or speeds, ballast or improper loading, elevated weights, etc.) could be considered.

With regards to the new stability developments at IMO, the 'traditional' stability criteria have the advantage of responding to the demands of these two points, as traditional criteria are based on the characteristics of vessels with a proven satisfactory stability performance in real operating conditions.

On the other hand the new approach proposed in IMO allows anticipating ship performance in certain situations not contemplated by current regulations.

Moreover, in the opinion of the author, the great conceptual contribution provided by the new stability developments at IMO is breaking the link that was implicit in the existing regulations between ship safety and stability curve features.

Under the author opinion, the best stability rules to ensure fishing vessels (and ships in general) safety should respond to the following characteristics:

- They must be based on the performance of existing ships, as the best way of ensuring that real operating conditions of vessels at sea are dealt with. They should not be limited to examining the characteristics of the stability curve; they must study the performance of ships against any failure mode.

- They need to be updated frequently, to catch the performance of newer ships.

- They should be suitable to assess the implications on the stability of the changes in the rules and regulations governing fishing activities.

It is technically possible to study on real-time the stability of small fishing vessels in the same way they are monitored by fishing authorities; the equipment on board can provide real time heeling values, and be stored and transmitted via radio for its study.

These tasks could be achieved by establishing a small office or Government Department dedicated to the monitoring of the stability of fishing vessels of the Spanish fleet, the constant updating of the criteria for stability of fishing vessels, and the surveillance of any rules of national or regional scope, which may have implications on the stability.

Our seamen and fishermen are worth it.

Madrid, june 05th 2014

8. THESIS PUBLICATIONS

8.1. Refereed papers

1. Mata-Alvarez-Santullano, F., Souto-Iglesias, A., 2014. Stability, safety and operability of small fishing vessels. Ocean Engineering 79, 81–91. DOI:10.1016/j.oceaneng.2014.01.011. JCR Science Edition. Impact factor 2012: 1.161. Quartile in category ENGINEERING, OCEAN: Q1 (3/15). Quartile in category ENGINEERING, MARINE: Q1 (2/14).

2. Mata-Alvarez-Santullano, F., Souto-Iglesias, A., 2013. Fishing effort control policies and ship stability: Analysis of a string of accidents in Spain in the period 2004–2007. Marine Policy Vol 40, 2013, pp 10–17. DOI: 10.1016/j.marpol.2012.12.027. Impact factor 2012: 2.230. Quartile in Category INTERNATIONAL RELATIONS: Q1 (5/83).

8.2. Conference papers

1. Mata-Alvarez-Santullano, F., Souto-Iglesias, A., 2013. Safety and operability of small fishing vessels: study of a series of stability-related accidents, in: Developments in Maritime Transportation and Exploitation of Sea Resources. Presented at the IMAM 2013 - International Maritime Association of the Mediterranean Congress 2013, CRC PRESS / BALKEMA, A Coruña. (Presented by the candidate)

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