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Evaluation of risk from watertight doors

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Task and objective:

The objective of this task is to perform assessment of risks to life arising due to the operation of watertight doors on board passenger ships, and to identify possible options for reducing this risk.

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1 PREFACE

This report is a deliverable according to the Framework Service Contract Number EMSA/OP/10/2013. This is the third study commissioned by EMSA related to the damage stability of passenger ships. The previous studies focused on ro-ro passenger (RoPax) ships. This study aims at further investigating the damage stability in an FSA framework in order to cover the knowledge gaps that have been identified after the finalization of the previous EMSA studies and the GOALDS project.

The project is separated in to 6 studies:

- Identification and evaluation of risk acceptance and cost-benefit criteria and application to risk based collision damage stability
- Evaluation of risk from watertight doors and risk based mitigating measures
- Evaluation of raking damages due to groundings and possible amendments to the damage stability framework
- Assessment of cost effectiveness or previous parts, FSA compilation and recommendations for decision making
- Impact assessment compilation
- Updating of the results obtained from the GOALDS project according to the latest development in IMO.

The project is managed by DNV-GL and is established as a joint project which includes the following organisations:

Shipyards/designer:

Euroyards representing: Meyer Werft, Meyer Turku, STX-France and Fincantieri
Knud E. Hansen AS

Operators:

Royal Caribbean Cruises
Carnival Cruises
Color Line
Stena Line

Universities:

National Technical University of Athens
University of Strathclyde
University of Trieste

Consultants:

Safety at Sea

Software manufacturer:

Napa OY

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4 ABBREVIATIONS

WTD	watertight doors
VDR	voyage data recorder
N_{fleet}	number of ships in the fleet
FSA	formal safety assessment
V_{cn}	volume of spaces connected by opened WTD
V_{DH}	volue of DAMHULL (geometry used for stability assessment)
$V_{cn\,all}$	volume connected in case of all doors opened
A	attained index of subdivision
A^*	attained index of subdivision (no phases, no moments, final stage of flooding)
A^*_{opened}	attained index of subdivision calculated for specific set of doors opened
A^*_{closed}	the same as A^*, all doors assumed closed
A_{WTD}	attained index of subdivision after correcting for various assumptions of impact of WTDs
cdf_{ttc}	cumulative distribution function for time to capsize
Hs	significant wave height
equivalent A	equivalent of A, conditional on specific sea state Hs
$f_{Hs}(H)$	probability density distribution for occurrence of specific sea state Hs during collision
r^*	ratio $A^*_{opened}/A^*_{closed}$
$r(t)$	the ratio r^* corrected for crew actions
$r^*(t)$	the ratio r^* corrected for crew actions and reliability of WTD
t	time (minutes or hours)
$c(t)$	reduction factor of the impact of opening of the WTD due to crew action
dR	contribution to risk due to WTD operation, $\frac{1-r(t)\cdot A}{1-A}$
$F(t\|\eta,\beta)$	probability of a failure of a single component within some time t (in hours)
η,β	Weibull characteristics of components
$P_{failure}(t)$	probability of malfunction of the WTD in time of t hours
$P_k(k,n,p)$	probability that a specific number of k WTD among total of n number of WTD fail
$E_f(k)$	expected number of WTD that may fail during an accident

$E_s(k)$ expected number of WTD that would successfully function during an accident

$c^*(t)$ reduction factor of the impact of opening of the WTD due to crew action and reliability of WTD

n_d number of WTD

WEPROGR a numerical technique of computer system NAPA to account for effect of a specific opening on flooding extent, and therefore, on stability.

NAPA a computer system for performing naval architecture calculations.

5 EXECUTIVE SUMMARY

This project addressed the contribution of watertight doors to the portion of risk to life relating to incidents of collision, for Cruise and RoPax ship types. The contribution has been assessed based on the following tasks;

- review of historical data on WTDs operation on existing ships,
- mathematical modelling, numerical simulations, stability assessment,
- design development and optimisation for reduction of this risk contribution.

Patterns of watertight doors usage have been analysed based on data from on-board recording systems for Cruise and RoPax passenger ship types. It was observed that typically a number of one or more WTDs are in frequent use during voyages, and majority of doors remain opened in ports. It has been noted that use of WTD is affected by its category. Namely, the averaged proportion of time the C category doors remain opened at sea is 11% and for A or B category doors it is 60%, although permitting A category door opened for 100% of the time has also been observed. The averaged duration a C category door remained opened was 1.33 minutes, with some doors opened/closed within slightly shorter, and some within much longer time span.

Assessment of the impact of an opened WTD on stability has led to an observation that the impact of any one single door, while varying from door to door, was found to be small relative to the impact of a combination of doors left opened. Furthermore, it was noted that such impact on stability was then insensitive to category of doors comprising the combination, that is, an opened door of category C or A would degrade stability on average to an equal extent.

A simplified mathematical model was developed to quantify this impact based on only a handful of relevant parameters. Namely, the model is based on the number of WTDs, their category, volume of connected spaces, total buoyant volume of the ship, time of the crew response to flooding situation, duration of doors opening and closure, and the rates of WTD failures (reliability). The construct of this model was a result of a compromise between simplicity, robustness and the accuracy. It was found that the spread in results derived by the simplified mathematical model was of the order of +/- 20% from the results derived through expensive direct calculations. Some of the parameters such as the location are only taken into account indirectly through the connected volume.

The application of this parametric model on RoPax ships needs to be further investigated as the pros and cons of the inclusion of the cargo deck in the total buoyant volume has been discussed among the partners and the impact needs to be further investigated to improve robustness of the model.

Whilst it is recommended that further study continue on possible refinements of the proposed approach, it was found during the course of the ship design and optimisation tasks that reasonable trends can be identified and viable design improvements can be put forward on the basis of calculations by the proposed approach.

For instance, the design studies have confirmed that new ships can be designed without the need for category A doors with considerable risk reduction, a fact which also has been considered by SDC2 in its decision to remove for new ships the possibility of getting an exemption for watertight doors to keep them open while at sea. Installation of multiples of doors of B or A category can contribute to risk to life significantly, with observed 56% increased risk because of many such doors designed on Ship #1. Hence this observation alone bears significant potential for tangible risk reductions.

The analysis of the existing ships also highlights that in some designs the use of doors is vital for the operation of ships. In particular for RoPax vessels it is the only way to reach other parts of the ship during normal watch keeping, as the bulkhead deck is blocked by the cargo deck.

The sensitivity of the model to the input information allows stressing the importance of operational procedures onboard. Efficient and timely crew response to flooding situation can significantly reduce the risk to life of those onboard. Conversely, lack of appropriate training or inefficient operational procedures can significantly increase risk to life above levels tolerated by regulations. The mathematical model can aid disclosure of these risks for design as well as for daily ship operation, for better awareness and training.

Based on the analyses performed and/or contributed to by a team of design offices, ship yards, class societies, operators, and academic establishments participating in this study, the following set of recommendations is put forward for reduction of contribution to risk to life by installation and operation of watertight doors on ships.

Remove or minimize the number of category A or B doors.
Design doors only for expedient pass through.

This is the most cost-effective risk control option identified in this project. Type A and B doors need to be minimized not only on newly build ships but also for the existing fleet. It is assumed that the real-life ship operation of WTDs adheres to MSC.1/Circ.1380 guidelines.

Improve onboard monitoring to quantify impact of WTDs explicitly
Improve training for emergencies.

The mathematical model proposed facilitates robust quantitative assessment of impact of opening of door combination on the risk. Such disclosure can be used for training onboard, policing and culture development for prudent use of WTDs. It is expected that significant reduction in the frequency of usage of WTD can be achieved, and crew preparadness for effective management of undesirable events of flooding prioritised.

Crew preparedness resulting to closure of WTD immediately, with no longer delay than 2 minutes, is particularly potent risk control measure that can be implemented for existing fleet of ships.

Improve design guidelines

It is recommended that guidelines to designers and operators on minimisation of the number of watertight doors on Tank Top level, as well as arranging access to compartments below bulkhead deck through upper deck levels, be developed and promoted. To achieve this, a closer cooperation between operators and designers is needed already in the conceptual design phase to avoid any design which may require the frequent usage of WTD.

6 INTRODUCTION

This is the final report of Task 2. The objective of this task has been to perform assessment of risks to life arising due to the operation of watertight doors on board passenger ships, and to identify possible options for reducing this risk.

The risk assessment followed an FSA-based approach according to the FSA Guidelines MSC-MEPC.2/Circ 12.

The approach comprises use of operational information from on board logs, historical data on accidents to personnel, as well as bespoke analyses of risks and risk modelling.

This report documents developments in the following sub – tasks:

- Sub-task a) Historical data on operational practice
- Sub-task b) Risk method
- Sub-task c) Operational analyses of designed ships and risk control options
- Sub-task d) Recommendations

7 HISTORICAL DATA

The WTD are power-operated devices. As such they pose risk to life, due to potential to cause harm to personnel passing through doors, or due to reduction of ship stability.

A summary of historical observations of accidents involving watertight doors, together with analyses of patterns of watertight doors usage based on data from on-board recording systems for four ships listed in the table below, are presented in **Appendix 1**.

Table 1 Summary of data obtained.

	Loading data	Doors status data
Cruise 1	x	x
Cruise 2	x	x
RoPax 1	x	x
Ropax 2	x	x

All information acquired has been obtained on strictly anonymous basis.

The statistics considered of most relevance for the study were the averaged proportion of time doors remain opened, listed in Table 2, and the averaged duration of single operation of opening and closing a door, listed in Table 3. The averaged proportion of time the C category doors remain opened at sea is 11%, for B category doors it is 60%, and for A category door it is assumed 100%. The averaged duration a C category door remains opened is 1.33 minutes.

Table 2 Summary of frequencies of use of WTD of category A, B and C (please see Table 4 on page 22).

Class of doors	Ship	% of instances remaining opened (at port and at sea)	% of instances remaining opened (at sea only)
C	Cruise 1	11.4	10.3
C	RoPax 1	62.8	9.7
C	RoPax 2	27.6	12.3
B	Cruise 1	62.6	59.1
A	Cruise 1	61.6	61.7
A	RoPax 2	100.0	100.0

Table 3 Summary of expected values of duration of single C category WTD operation (opening and closing).

	duration doors opened [minutes] (at port and at sea)	duration doors opened [minutes] (at sea only)
Cruise 2	1.84	N/A
RoPax 1	1.49	0.43
RoPax 2	1.58	1.31

Data for Cruise 1 had frequency of recording of 2 hours, hence in excess of the above resolution. Data for Cruise 2 did not contain indicators of sail or port conditions.

The above data have been used as guidance for assumptions used for risk assessments described in subsequent part of the report.

8 RISK METHOD

One of the objectives of the project was to derive a risk model representing impact of patterns of usage of the WTD.

The risk modelling adopted reflects key elements of the approach adopted in Task 1 of the project, namely the proportionality of risk to the quantity of (1-A), where A is the attained index of subdivision.

In this task only the attained index for collision has been used, as any formulation for grounding was not finalized.

8.1 The reduction of index A

To derive the method, extensive calculations of sensitivity of the quantity of (1-A) were performed as summarised in **Appendix 2 and 3**.

For making the computations feasible, the calculations of index A were performed only for one single loading condition, and therefore the calculated index was considered as an “equivalent” index A*. Furthermore, the study involved also sensitivity tests of A* to sea state, as mentioned in **Appendix 2**.

The most significant observation from this exercise was that the impact of any one single door, while varying from door to door, was found to be small relative to the impact of a combination of doors left opened.

This observation inspired the risk method that was subsequently developed. The core objective of the method was to reflect the impact of a combination of watertight doors usage at any one time. Such method has been constructed after several iterations and with advice from designers.

The impact of use of WTD was quantified by means of reduction of the index A, conveniently expressed as the ratio $r^* = A^*_{opened}/A^*_{closed}$, where A^*_{opened} reflects the equivalent index A after one or several doors are opened, and A^*_{closed} reflects the equivalent index A with all doors closed, both calculated for final stages of flooding, and where available for a loading condition as recorded onboard.

The impact of use of a combination of WTD on this ratio, was found to be represented reasonably well by means of a ratio of total volume of watertight spaces connected by WTD that were opened, denoted as V_{cn}, to total volume considered buoyant, denoted often as DAMHULL and denoted as V_{DH} as shown by equation (1).

$$r^* = \frac{A^*_{opened}}{A^*_{closed}} = 1 - \frac{V_{cn}}{V_{DH}} \qquad (1)$$

8.2 Definitions of main design parameters

The value V_{cn} reflects the volumes of those spaces, which are connected by the WTD in question, see example Figure 1. Not only those spaces, which are directly adjacent to the door are to be considered (shown in dark blue), but also any space, which is flooded in subsequent stages via non-watertight structures or openings (shown in light blue).

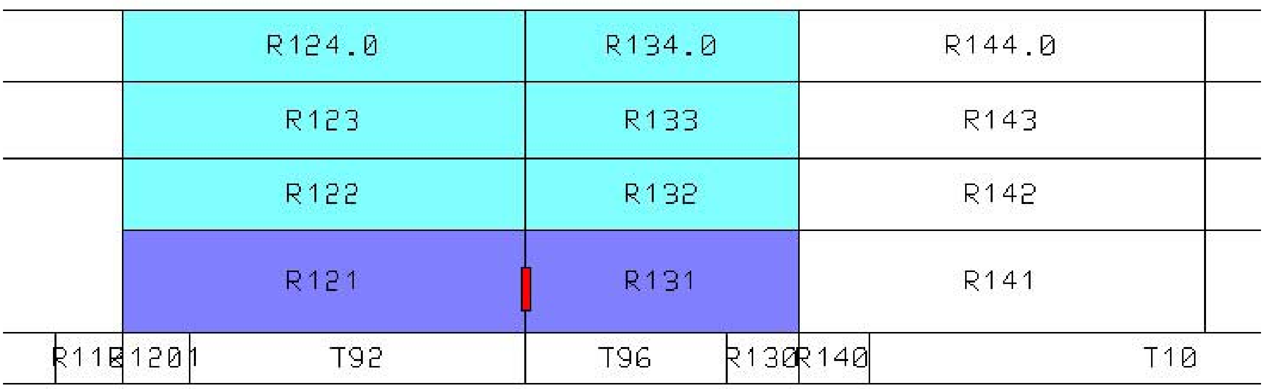

Figure 1 Definition of connected volumes.

If more than one open WTD is considered and the connected spaced would overlap, e.g. an additional door which would connect R131 and R141, the volume of those spaces which are connected via more than one door are only calculated once. If in RoPax ships the car deck is connected to any space below the bulkhead deck via openings or non-watertight structures, like A-class boundaries, the volume of the car deck is to be considered part of the connected volume, if a WTD connects the space below bulkhead deck with other spaces.

The V_{DH} is the overall moulded volume of the buoyant hull used in the damage stability calculation. The Figure 2 below shows a typical DAMHULL, which includes one deck above the bulkhead deck.

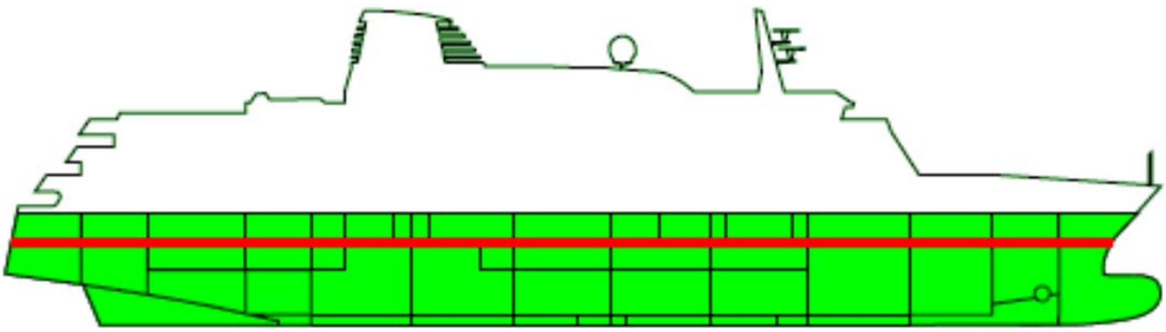

Figure 2 Extent of DAMHULL

In case of RoPax ships the car deck is usually included in the DAMHULL, as it is considered as part of the reserve buoyancy, reflecting realism of this function of these spaces for incidences such as for instance grounding.

8.3 Risk model

As mentioned above, calculations were performed for five design ships of Task 1, as summarised in **Appendix 2**, as well as for the two Cruise ships and two RoPax of Task 2, for deepest subdivision draught DS, with the results of $A^*_{opened}/A^*_{closed}$ presented as a function of the ratio V_{cn}/V_{DH}. Summary of these calculations is shown in Figure 3.

While a degree of spread can be observed, it was deemed by the project team as a viable tool for the assessment of impact of WTDs. The range of uncertainty of the method has been quantified as a spread between calculations of impact of WTD doors based on one hand on the averaged parametric model (1), and based on the direct stability calculations for the actual spaces flooded after WTD remain opened, on the other. The spread in results derived by mathematical fit model (1) was found to be of the order of +/- 20% from the direct calculations, as shown in Figure 4.

8.3.1 Crew actions

To extend the model for the impact of crew actions during emergency, a correction factor was developed as described in **Appendix 3**. Considering the crew actions modelled by factor (11), the net impact of WTD may be represented by ratio $r^* \equiv r(t)$ as shown by equation (2), where t refers to time to close WTD doors in minutes.

$$r(t) = 1 - c(t) \cdot \frac{V_{cn}}{V_{DH}} \qquad (2)$$

Where for convenience the factor (11) is repeated as equation (3):

$$c(t) = 1.047 \cdot \left(1 - e^{-0.104 \cdot t}\right) \qquad (3)$$

8.3.2 Reliability

Furthermore, the impact of reliability of WTD was derived as described in **Appendix 4**. The correction for reliability has been proposed to be applied as correction to equation (3), as follows.

$$c^*(t) = P_{failure}(1year) + \left(1 - P_{failure}(1year)\right) \cdot c(t) \qquad (4)$$

Where the $P_{failure}(1year)$ ·is an average annual failure rate of a single watertight door.

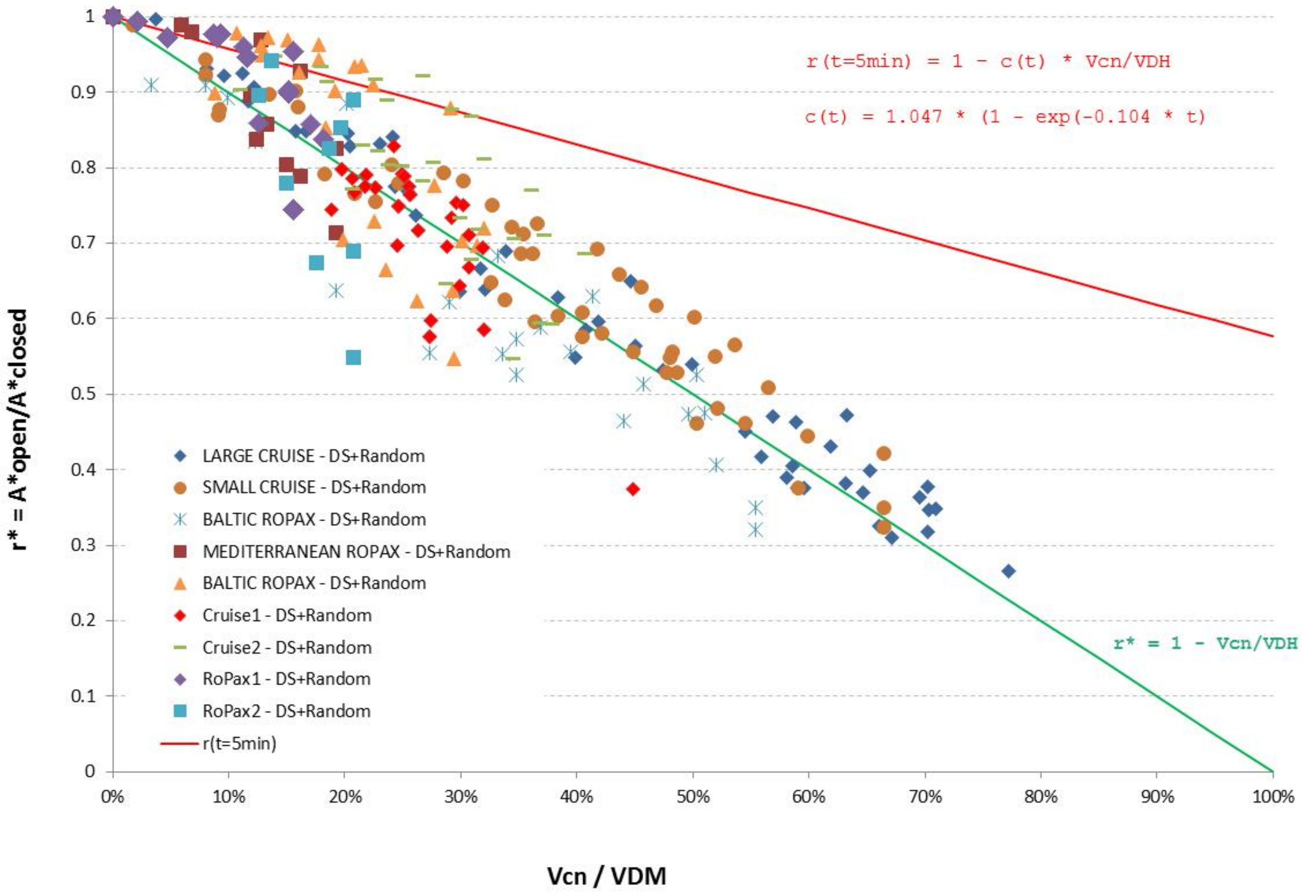

Figure 3 Relationship between reduction in survivability due to WTD operation, $A^{*}_{opened}/A^{*}_{closed}$, and the ratio of volumes, V_{cn}/V_{DH}.

The impact of time to close on this ratio is shown by red line.

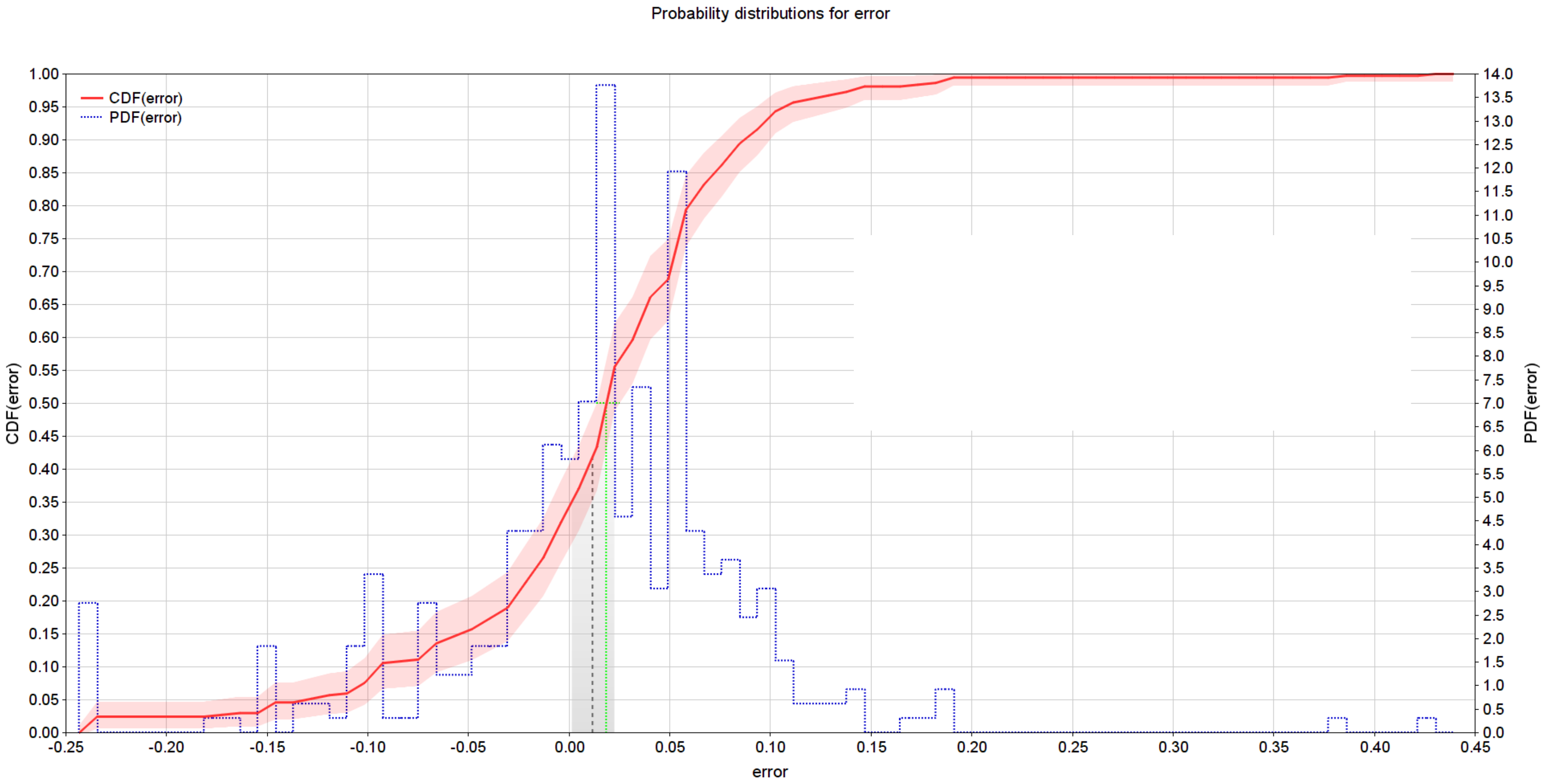

Figure 4 Spread between regression model and direct calculations of $A^{*}_{opened}/A^{*}_{closed}$.

The spread indicates an uncertainty range of the regression model (2).

8.3.3 Application of the model for design purposes

To quantify different risk control options the above methodology needed to be extended further for practical use.

To accommodate for the intent of the regulations as regards doors operation, WTD categorisation as defined in MSC. 1/Circ. 1380, listed in Table 4, has been used to estimate the percentage in time when any door may be opened.

Table 4 Door categories according MSC.1/Circ.1380

Category	Definition	Open while atsea
A	A watertight door that fulfils the technical requirements in SOLAS regulations II-1/13.5.1 to 13.5.3 and 13.6 which also includes the requirements in paragraph 7 of SOLAS regulation II-1/13,	The door is permitted to remain open during navigation by the Administration according to SOLAS regulation II-1/22.4
B	A watertight door that fulfils the technical requirements in SOLAS regulations II-1/13.5.1 to 13.5.3 and 13.6 which also includes the requirements in paragraph 7 of SOLAS regulation II-1/13	The door may be opened during navigation when work in the immediate vicinity of the door necessitates it being opened, according to SOLAS regulation II-1/22.3 . The door must be immediately closed when the task which necessitated it being open is finished.
C	A watertight door that fulfils the technical requirements in SOLAS regulations II-1/13.5.1 to 13.5.3 and 13.6 ,which also includes the requirements in paragraph 7 of SOLAS regulation II-1/13.	The door may be opened during navigation to permit the passage of passengers or crew, according to SOLAS regulation II-1/22.3. The door must be immediately closed when transit through the door is complete.
D	A watertight door that does not comply with SOLAS regulations II-1/13.5.1 to 13.5.3 and 13.6, which also includes the requirements in paragraph 7 of SOLAS regulation II-1/13	The door shall be closed before the voyage commences and shall be kept closed during navigation according to SOLAS regulation II-1/22.1.

The frequency of usage of doors of different categories is summarised in Table 2 and paragraph 7.

Currently, doors of category D do not comply with the requirements relating to WTD, and therefore, such doors need to be closed before leaving port. Doors with this new category are now defined to be closed during normal operation, they are not even opened for passage, but they are only used as secondary means of escape. They will comply with the other requirements for WTD as stated in regulation II-1/13.

To prevent any unintended use, any opening of the door should cause a fire alarm.

Although the recordings of the existing ships do not show a clear relation between the door category and the usage while at sea, the team has decided to define for each of the door category a percentage in time, based on the experiences of the operators, but also to reflect the intention of the regulations. On the other hand the time to close a door is to be considered and may vary significantly between the different categories of the doors.

Furthermore, the number of doors in total may influence the risk and the requirement of SOLAS II-1/13 should be quantified:

> *Regulation 13 - Openings in watertight bulkheads below the bulkhead deck in passenger ships*
> *1. The number of openings in watertight bulkheads shall be reduced to the minimum compatible with the design and proper working of the ship, satisfactory means shall be provided for closing these openings.*

Based on these assumptions the formulation (2) has been modified into (5), and applied to the sample ships including the risk control options.

$$r^* = \frac{A^*_{opened}}{A^*_{closed}} = 1 - b * \frac{V_{cnall}}{V_{DH}} \qquad (5)$$

Where *b* is the mean reduction of risk due to the categories and use of doors defined as the following equation (6).

$$b = \frac{\sum_{i=1}^{n_{door}} P_{WTD\,i} * c(t_i) * V_{cn\,i}}{\sum_{i=1}^{n_{door}} V_{cn\,i}} \qquad (6)$$

Where:

n_{door}	total number of WTD
$P_{WTD\,i}$	probability that a door is open at a certain point of time, for given door category as proposed in Table 5.
$c(t_i)$	impact of crew actions according to (3) or (4), for time t_i
t_i	assumed closure of WTD as proposed in Table 5
$V_{cn\,i}$	volume connected to a given WTD, calculated for this door opened only
$V_{cn\,all}$	volume connected in case of all doors opened

Table 5 Proposal for operational parameters of WTD of various categories.

Door Category	Description of category	Probability that a door is open at a certain point of time $P_{WTD\,i}$	Time to close the door, t_i
A	Door permitted to stay open at sea	100%	5 minutes
B	Door which may be opened during work in the vicinity of the door	60%	3 minutes
C	Door which may be used to pass through	11%	1 minute
D	Door which is always closed – this is proposal of a new door category	0%	0 minute

8.3.4 Risk contribution due to daily operations

Further contribution to risk from the WTD operations derives from accidents involving passage through doors.

As mentioned in **Appendix 1**, the approximate rate of 1 fatality per year is observed by insurance providers. Such rate in a fleet of ships comprising N_{fleet} of ships, contributes to the risk a $1/N_{fleet}$ fatalities per ship per year.

This contribution is considered negligible, and it is omitted from risk calculations.

9 OPERATIONAL ANALYSES OF DESIGNED SHIPS AND RISK CONTROL OPTIONS

New designs of six passenger ships have been developed in Task 1, [23], to form the basis for the optimization and benchmark for the subdivision index, as well as for grounding and the effect of open watertight doors.

All designs comply with the current statutory rules and regulations, e.g. SOLAS2009 including SRtP where applicable. The designs have been selected in close cooperation between the designers and ship operators, and represent the world fleet. Each design has been optimized with regard to the attained index for collision, taking into account the agreed limits for cost effectiveness.

In this task the impact of open watertight doors has been analysed for all the sample ships (except double ended ferry), whilst RCOs have been studied for all but the Mediterranean RoPax and the double end ferry, as summarised in Table 6. A method has been developed to use the parametric model to judge the risk control options against the limits of cost effectiveness. The cost calculations are based on the same approach as that used in Task 1. However, the impact on operation has been estimated by the operators.

Table 6 List of sample ships for task 2.

No	Type	Length bp	Breadth	Draught	Gross Tonnage	Number of Persons
1	large Cruise	300.00 m	40.80 m	8.75 m	153400	6730
2	small Cruise	113.70 m	20.10 m	5.30 m	11834	478
3	RoPax baltic	232.00 m	29.00 m	7.20 m	60000	3280
5	RoPax ferry	95.95 m	20.20 m	4.90 m	7900	625

Each of the sample ship is presented in detail with its reference design in the report of Task 1.

The detailed designs have been developed by design teams consisting of a shipyard/designer and an operator for each ship. The design versions are described in more detail in the following chapters.

9.1 Ship #1 Large Cruise Ship

9.1.1 Location of WTD

The reference design of this ship has 35 watertight doors in total, as listed in Table 7 and shown Figure 5. It reflects a typical design of modern cruise ships, where watertight doors are used for several reasons. Many doors are the second means of escape, where only one enclosed staircase is provided in the watertight compartment. Other doors are needed to allow the transportation of goods during daily operation, for instance between the lifts and the provision rooms, or for maintenance and transport of spare parts, for instance in the engine rooms.

In spaces above the bulkhead deck on deck 4 the watertight doors are installed in the partial bulkheads which are mostly located directly on top of a watertight bulkhead to prevent progressive flooding along the bulkhead deck.

Depending on the purpose, the door categories are defined together with the operator.

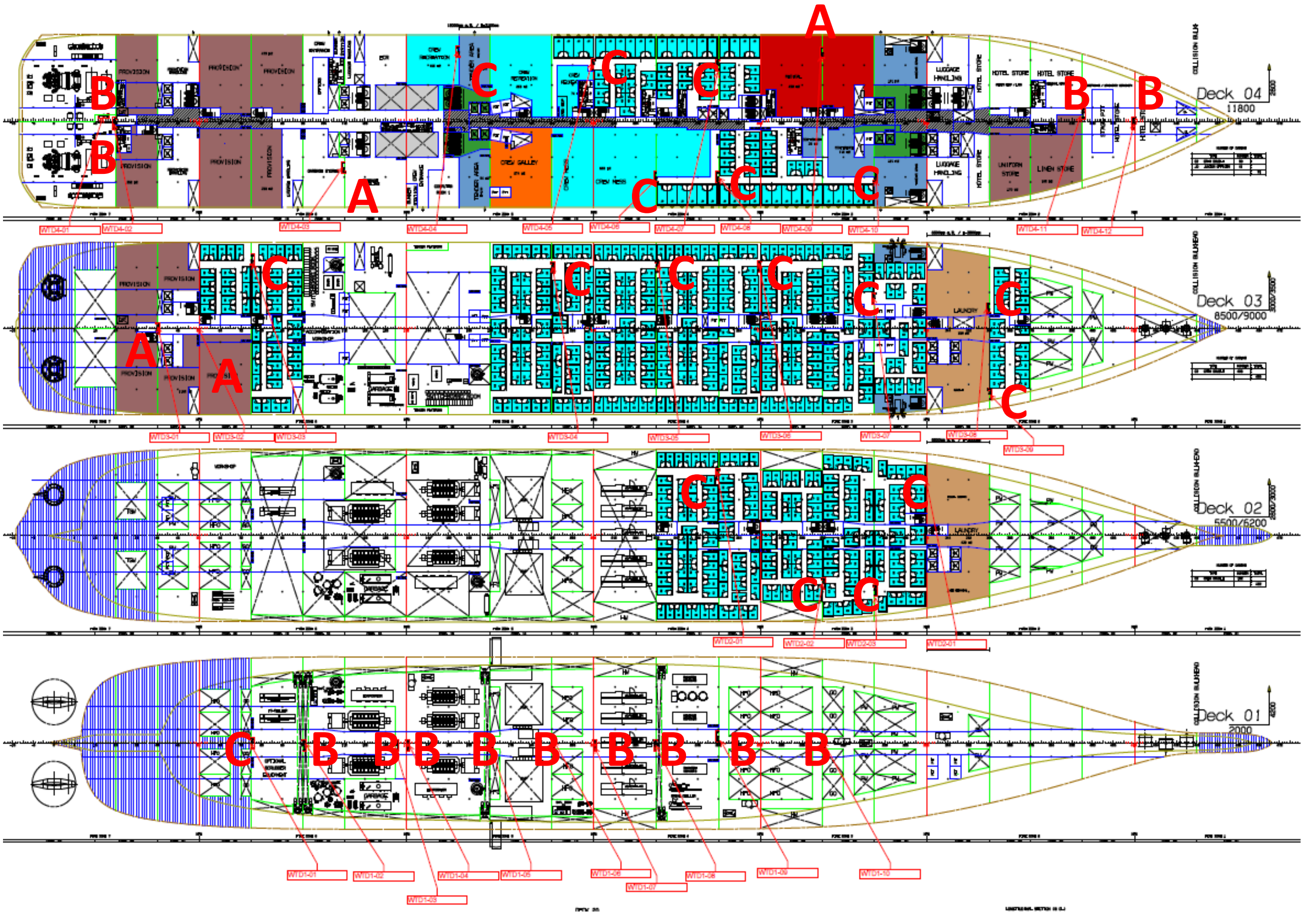

Figure 5 Ship 1 – location and category of WTD.

Table 7 Ship 1 – list of WTD.

ID	Deck	category
WTD101	Deck 1	C
WTD102	Deck 1	B
WTD103	Deck 1	B
WTD104	Deck 1	B
WTD105	Deck 1	B
WTD106	Deck 1	B
WTD107	Deck 1	B
WTD108	Deck 1	B
WTD109	Deck 1	B

WTD110	Deck 1	B
WTD201	Deck 2	C
WTD202	Deck 2	C
WTD203	Deck 2	C
WTD204	Deck 2	C
WTD301	Deck 3	A
WTD302	Deck 3	A
WTD303	Deck 3	C
WTD304	Deck 3	C
WTD305	Deck 3	C
WTD306	Deck 3	C
WTD307	Deck 3	C
WTD308	Deck 3	C
WTD309	Deck 3	C
WTD401	Deck 4	B
WTD402	Deck 4	B
WTD403	Deck 4	A
WTD404	Deck 4	C
WTD405	Deck 4	C
WTD406	Deck 4	C
WTD407	Deck 4	C
WTD408	Deck 4	C
WTD409	Deck 4	A
WTD410	Deck 4	C
WTD411	Deck 4	B
WTD412	Deck 4	B

9.1.1.1 Investigated design variations

The considerations of risk control options are driven by the factors which influence the overall risk contribution due to WTDs. Viable options for control of risk comprise removal of watertight doors, minimisation of the volume connected by WTDs, or minimisation of the frequency that any door is used while at sea.

The following table summarises an overview of the applied design variations, with more detailed description presented in the subsequent pages.

Table 8 Ship 1 – design variations.

Version	Description
G2	Reference version
G4	Removal of WTDs
G5	Assigning new door categories
G6	Removal of WTDs and assigning new door categories

9.1.1.2 Version G2 – reference design

The following Table 9 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version G2.

Table 9 Ship 1 - Version G2, risk calculations.

Ver G2 Reference Version	
Index A (SOLAS2009)	0.8622
Volume of DAMHULL, V_{DH}	175374
$V_{cn\ all}$	135364
$V_{cn\ all}$ / V_{DH}	0.77186
Number of WTD	35
b	0.11624
r*	0.91028
A_{WTD}	0.78484

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.038725067	C	0.11	0.10312849
WTD102	0.053150889	B	0.6	0.27990037
WTD103	0.042387457	B	0.6	0.27990037
WTD104	0.053582218	B	0.6	0.27990037
WTD105	0.058467228	B	0.6	0.27990037
WTD106	0.038490649	B	0.6	0.27990037
WTD107	0.038574779	B	0.6	0.27990037
WTD108	0.050620998	B	0.6	0.27990037
WTD109	0.042325988	B	0.6	0.27990037
WTD110	0.040957247	B	0.6	0.27990037
WTD201	0.033069604	C	0.11	0.10312849
WTD202	0.035525523	C	0.11	0.10312849
WTD203	0.032600247	C	0.11	0.10312849
WTD204	0.034789971	C	0.11	0.10312849
WTD301	0.020258505	A	1	0.42355089
WTD302	0.022917899	A	1	0.42355089
WTD303	0.025287865	C	0.11	0.10312849
WTD304	0.025288438	C	0.11	0.10312849
WTD305	0.030317016	C	0.11	0.10312849
WTD306	0.025433829	C	0.11	0.10312849
WTD307	0.025227723	C	0.11	0.10312849

WTD308	0.024609589	C	0.11	0.10312849
WTD309	0.024609589	C	0.11	0.10312849
WTD401	0.00972423	B	0.6	0.27990037
WTD402	0.012971544	B	0.6	0.27990037
WTD403	0.016255818	A	1	0.42355089
WTD404	0.012883377	C	0.11	0.10312849
WTD405	0.017048802	C	0.11	0.10312849
WTD406	0.020322449	C	0.11	0.10312849
WTD407	0.016951597	C	0.11	0.10312849
WTD408	0.016951597	C	0.11	0.10312849
WTD409	0.01863701	A	1	0.42355089
WTD410	0.017938679	C	0.11	0.10312849
WTD411	0.012997304	B	0.6	0.27990037
WTD412	0.010099273	B	0.6	0.27990037

9.1.1.3 Version G4 – removal of WTDs

In this version a number of water tight doors have been removed. The primary purpose of the doors was the secondary means of escape. This function can also be provided by vertical emergency exits or additional stairways leading up to the bulkhead deck. Such secondary escape routes do not need to be enclosed by staircases. Also, the requirements on minimum stair widths do not apply.

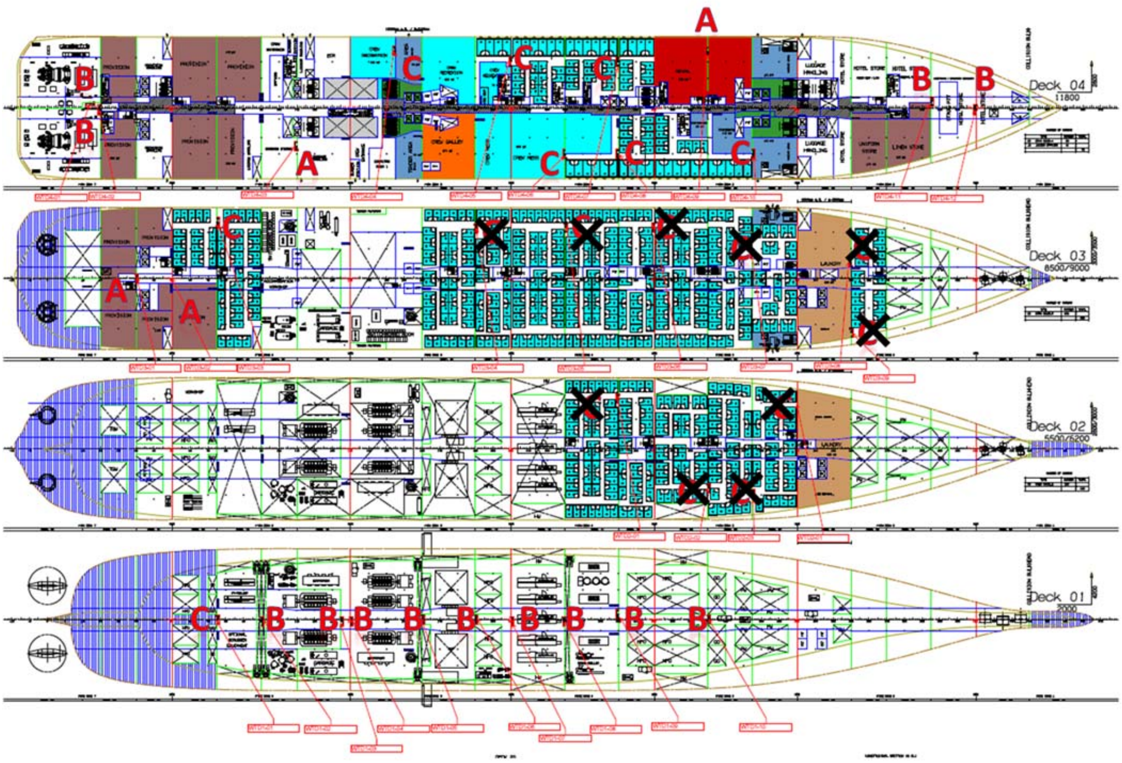

Figure 6 Ship 1 – Version G4, WTD arrangement.

The consequence for such a change would be that for each of the compartments below the bulkhead deck where crew cabins are located an additional stairway is to be provided. This is the main reason for additional costs, as listed in Table 10.

Table 10 Ship 1 – Version G4, cost assessment.

Total Costs for Investment			CAPEX	-129,600 €
Total Change of operational costs			OPEX	0 €
Total Change of annual revenue			REVENUE	-527,693 €

Calculation of investment costs				
	size	Unit	spec value	costs
Costs for financing, insurance etc	-120,000 €	€	8%	-9,600 €
Add steel stair cases	10	t	6,000	60,000 €
Deleted WTDs	10		-18,000	-180,000 €

Calculation of revenue				
	size	Unit	spec value	costs
Loss of passenger cabins	-5		105,538.52	-527,693 $

The effect on operational procedures is assumed to be very small, as these doors are not used for transport or service functions. The space required for the additional stairs would mean a reduction of crew cabins. Approximately 15 crew cabins with 30 crew berths are lost. It can be assumed that this can only be compensated by removal of 5 passenger cabins with the loss of revenue.

The following Table 11 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version G4.

Table 11 Ship 1 – Version G4, risk calculations.

Ver G4 removal of WTD	
Index A (SOLAS2009)	0.8622
Volume of DAMHULL, V_{DH}	175,374
$V_{cn\ all}$	122,164
$V_{cn\ all}$ / V_{DH}	0.69659
Number of WTD	25
b	0.09196
r*	0.93594
A_{WTD}	0.80697

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.038725	C	0.11	0.10312849
WTD102	0.053151	B	0.6	0.27990037
WTD103	0.042387	B	0.6	0.27990037
WTD104	0.053582	B	0.6	0.27990037
WTD105	0.058467	B	0.6	0.27990037
WTD106	0.038491	B	0.6	0.27990037
WTD107	0.038575	B	0.6	0.27990037
WTD108	0.050621	C	0.11	0.10312849
WTD109	0.042326	C	0.11	0.10312849
WTD110	0.040957	C	0.11	0.10312849
WTD301	0.020259	A	1	0.42355089
WTD302	0.022918	A	1	0.42355089
WTD303	0.025288	C	0.11	0.10312849
WTD401	0.009724	B	0.6	0.27990037
WTD402	0.012972	B	0.6	0.27990037
WTD403	0.016256	A	1	0.42355089
WTD404	0.012883	C	0.11	0.10312849
WTD405	0.017049	C	0.11	0.10312849
WTD406	0.020322	C	0.11	0.10312849
WTD407	0.016952	C	0.11	0.10312849
WTD408	0.016952	C	0.11	0.10312849
WTD409	0.018637	A	1	0.42355089
WTD410	0.017939	C	0.11	0.10312849
WTD411	0.012997	B	0.6	0.27990037
WTD412	0.010099	B	0.6	0.27990037

9.1.1.4 Version G5 – change of doors categories.

In this version the selected risk control option is to use other categories of the WTDs.
Two different solutions have been used. Namely, all A category doors have been removed, and a new door category D has been introduced.
Doors which may be assigned to have category D could be doors between watertight compartments where the crew accommodation is located. These compartments have always vertical stairways up to the bulkhead deck, and no passage through these doors would impede the normal operation on board.

The doors, which have been reassigned from category C to D, are shown in the Table 13.

The change of category A doors to B is more complicated and has more influence on design.

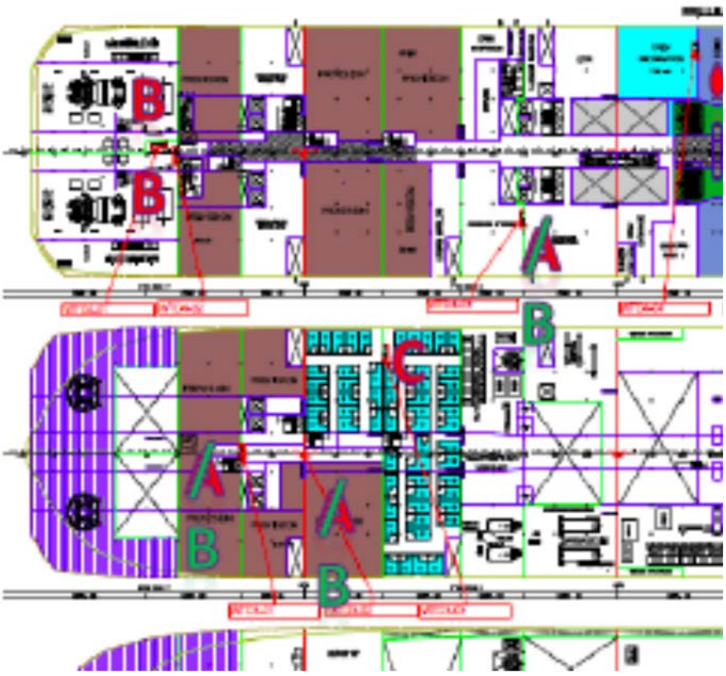

Figure 7 Ship 1 - Version G5, removal of A doors

The doors in question connect the provision rooms below the bulkhead deck. The doors are now used to allow the transport from the provision rooms to the service lifts leading to the main galleys above. If the doors are re- categorised then two additional platform lifts need to be installed to allow the transport up to the bulkhead deck and then onward to the main galley. This seems to be the easier solution than to remove the watertight bulkhead and to form one large watertight compartment. The costs for the additional platform lifts are shown in the Table 12.

Table 12 Ship 1 - Version G5, costs assessment.

			CAPEX	237,600 €
			OPEX	0 €
			REVENUE	0 €

Calculation of investment costs				
	size	Unit	spec value	costs
Costs for financing, insurance etc	220,000 €	€	8%	17,600 €
Platformlifts	2		110,000	220,000 €

The two doors on the bulkhead deck, which are of A category in the reference version, can be re-categorized easily. It implies somewhat more complicated operation, as the garbage needs to be transported via the main service corridor from the garbage stores to the garbage handling room.

The door connecting both parts of the medical centre can also be re- categorised, as a different operation of the medical centre can minimize the use of the door.

Alternatively for both doors above the bulkhead deck the partial bulkhead could be removed and additional watertight decks could be introduced. This option has not been considered in detail, as it may have some negative impact on the attained index and it would imply additional costs.

The following Table 13 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version G5.

Table 13 Ship 1 - Version G5, risk calculations.

Ver G5	
change of door categories	
Index A (SOLAS2009)	0.8622
Volume of DAMHULL, V_{DH}	175,374
$V_{cn\ all}$	135,364
$V_{cn\ all}$ / V_{DH}	0.77186
Number of WTD	35
b	0.05765
r*	0.95551
A_{WTD}	0.82384

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.038725	C	0.11	0.10312849
WTD102	0.053151	C	0.11	0.10312849
WTD103	0.042387	B	0.6	0.27990037
WTD104	0.053582	B	0.6	0.27990037
WTD105	0.058467	B	0.6	0.27990037
WTD106	0.038491	B	0.6	0.27990037
WTD107	0.038575	C	0.11	0.10312849
WTD108	0.050621	C	0.11	0.10312849
WTD109	0.042326	C	0.11	0.10312849
WTD110	0.040957	C	0.11	0.10312849
WTD201	0.033070	D	0	0
WTD202	0.035526	D	0	0
WTD203	0.032600	D	0	0
WTD204	0.034790	D	0	0
WTD301	0.020259	B	0.6	0.27990037
WTD302	0.022918	B	0.6	0.27990037
WTD303	0.025288	C	0.11	0.10312849
WTD304	0.025288	D	0	0
WTD305	0.030317	D	0	0
WTD306	0.025434	D	0	0
WTD307	0.025228	D	0	0
WTD308	0.024610	D	0	0
WTD309	0.024610	D	0	0
WTD401	0.009724	B	0.6	0.27990037
WTD402	0.012972	B	0.6	0.27990037

WTD403	0.016256	B	0.6	0.27990037
WTD404	0.012883	C	0.11	0.10312849
WTD405	0.017049	C	0.11	0.10312849
WTD406	0.020322	C	0.11	0.10312849
WTD407	0.016952	C	0.11	0.10312849
WTD408	0.016952	C	0.11	0.10312849
WTD409	0.018637	B	0.6	0.27990037
WTD410	0.017939	C	0.11	0.10312849
WTD411	0.012997	B	0.6	0.27990037
WTD412	0.010099	B	0.6	0.27990037

9.1.1.5 Version G6 - change of door categories and removal of doors

The version G6 is a combination of the alternative versions G4 and G5. Some doors are removed, and various doors are re- categorised. The cost calculations are shown in Table 14.

Table 14 Ship 1 – Version G6, costs estimates.

			CAPEX	108,000 €
			OPEX	0 €
			REVENUE	-527,693 €

Calculation of investment costs				
	size	Unit	spec value	costs
Costs for financing, insurance etc	100,000 €	€	8%	8,000 €
Add steel stair cases	10	t	6000	60,000 €
Deleted WTDs	10		-18,000	-180,000 €
Platformlifts	2		110,000	220,000 €

Calculation of revenue				
	size	Unit	spec value	costs
Loss of passenger cabins	-5		105,538.52	-527,693 €

The following Table 15 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version G6.

Table 15 Ship 1 - Version G6, risk calculations.

change of door categories and removal of doors	
Index A (SOLAS2009)	0.8622
Volume of DAMHULL, V_{DH}	175,374
$V_{cn\ all}$	122,164
$V_{cn\ all}$ / V_{DH}	0.69659
Number of WTD	25
b	0.05765
r*	0.95984
A_{WTD}	0.82758

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.038725	C	0.11	0.10312849
WTD102	0.053151	C	0.11	0.10312849
WTD103	0.042387	B	0.6	0.27990037
WTD104	0.053582	B	0.6	0.27990037
WTD105	0.058467	B	0.6	0.27990037
WTD106	0.038491	B	0.6	0.27990037
WTD107	0.038575	C	0.11	0.10312849
WTD108	0.050621	C	0.11	0.10312849
WTD109	0.042326	C	0.11	0.10312849
WTD110	0.040957	C	0.11	0.10312849
WTD301	0.020259	B	0.6	0.27990037
WTD302	0.022918	B	0.6	0.27990037
WTD303	0.025288	C	0.11	0.10312849
WTD401	0.009724	B	0.6	0.27990037
WTD402	0.012972	B	0.6	0.27990037
WTD403	0.016256	B	0.6	0.27990037
WTD404	0.012883	C	0.11	0.10312849
WTD405	0.017049	C	0.11	0.10312849
WTD406	0.020322	C	0.11	0.10312849
WTD407	0.016952	C	0.11	0.10312849
WTD408	0.016952	C	0.11	0.10312849
WTD409	0.018637	B	0.6	0.27990037
WTD410	0.017939	C	0.11	0.10312849
WTD411	0.012997	B	0.6	0.27990037
WTD412	0.010099	B	0.6	0.27990037

9.1.1.6 Comparison of results

The overview of the results is shown in the Table 16.

Table 16 Ship 1 – overview of results of risk calculation.

Version	Description	A SOLAS2009	A_{WTD}	ΔA_{WTD} difference with respect to reference version
G2	Reference version	0.8622	0.7848	0.0000
G4	Removal of WTDs	0.8622	0.8070	0.0221
G5	Assigning new door categories	0.8622	0.8238	0.0390
G6	Removal of WTDs and assigning new door categories	0.8622	0.8276	0.0427

9.1.2 Cost Benefit Assessment

The cost benefit assessment is based on the same assumptions as in task 1 for collision. Also the ΔPLL is calculated based on the risk model for collision as the parametric model is also based on the attained index for collision. The costs of each RCO has been shown in Euro and transferred to USD using a constant rate of exchange of 1.35 $/€.

The overview of the costs for the different RCOs can be seen in the Table 17.

Table 17 Ship 1 – summary of cost benefit assessment.

Version	G2	G4	G5	G6
description	Reference version	Removal of WTDs	Assigning new door categories	Removal of WTDs and assigning new door categories
attained index A Collision	0.8622	0.8622	0.8622	0.8622
A_{WTD}	0.7848	0.8070	0.8238	0.8276
change A	0.0000	0.0221	0.0390	0.0427
NetCAF = 4 Mio $	0 $	1,191,124 $	2,099,472 $	2,300,886 $
NetCAF = 8 Mio $	0 $	2,382,247 $	4,198,945 $	4,601,772 $
Net Present Value NPV	0 $	11,323,699 $	320,760 $	11,644,459 $

It can be seen that the removal of doors has a significant impact on space and will result in a loss of passenger cabins. The space requirement is based on the additional stairway to be installed in each of the watertight compartments. The loss of revenue due to the loss of passenger cabins immediately leads to very high costs which are far beyond the netCAF limits.

The netCAF limits are relatively small due to the small ΔPLL based on the small change of index A.

However, the new categorization of doors including the removal of any A category door is within the limits of cost effectiveness.

9.1.3 Summary

The results of this investigation need some explanation. It seems surprising that the removal of watertight doors shows little or no positive effect on the attained index, contrary to intuitive expectation.

The main reason for this may derive from the nature of the parametric model, which represents an averaged impact of any watertight door, rather than reflecting the specific impact of any one door or a combination thereof. The averaging is achieved through both the factor b and the ratio of volume connected to total buoyant volume, V_{cn}/V_{DH}.

In a particular case of this ship, despite removal of some of the C category doors the averaged value of b actually increased, and this due to the increased proportion of A and B doors among doors left. Furthermore, although 10 out of 35 doors have been removed, which is 29%, the connected volume $V_{cn\ all}$ only decreased by 9%. The reason for the latter is in fact as expected, as due to multiple watertight doors in certain watertight bulkheads these compartments are accounted for in the calculation of $V_{cn\ all}$.

Therefore, whilst the results are reflecting the adopted assumptions and modelling of the parametric formulation consistently, the approximations adopted to address the issue of the large number of combinations pose some limits, which need careful monitoring when applying the method. As mentioned in chapter 8, it is expected that the parametric model reflects the impact of some specific combination of opened doors to within +/- 20% accuracy with respect to the impact calculated exactly for every such combination.

Despite these limitations, the findings from the analyses of different RCOs appear as expected regarding ways to minimize the risk due to watertight doors. It appears that the removal of any A category door and the use of the new category D, a door which may only be used in case of emergency as a secondary means of escape, present viable RCO within the limits for cost effectiveness. On the other hand removal of watertight doors results in this ship to additional space requirements due to the need to provide a secondary means of escape from each watertight compartment, which immediately results in a loss of revenue space and thus exceeding the netCAF limits substantially.

9.2 Ship #2 Small Cruise Ship

9.2.1 Location of WTD

An initial design of this ship has 11 watertight doors in total, as listed in Table 18 and Figure 8. Six of them are located on deck 2 (deck below bulkhead deck) and they are provided as second means of escape. Other doors are located on deck 1 in the engine rooms and aux rooms. Those doors are provided for the daily work in order to guarantee the passage between the machinery spaces during daily operations and the movement of spare parts.

Depending on the purpose the door categories are defined together with the operator.

Table 18 Ship 2 - list of WTD.

ID	Deck	category
WTD101	Deck 1	C
WTD102	Deck 1	C
WTD103	Deck 1	B
WTD104	Deck 1	B
WTD105	Deck 1	B
WTD201	Deck 2	C
WTD202	Deck 2	C
WTD203	Deck 2	C
WTD204	Deck 2	C
WTD205	Deck 2	C
WTD206	Deck 2	C

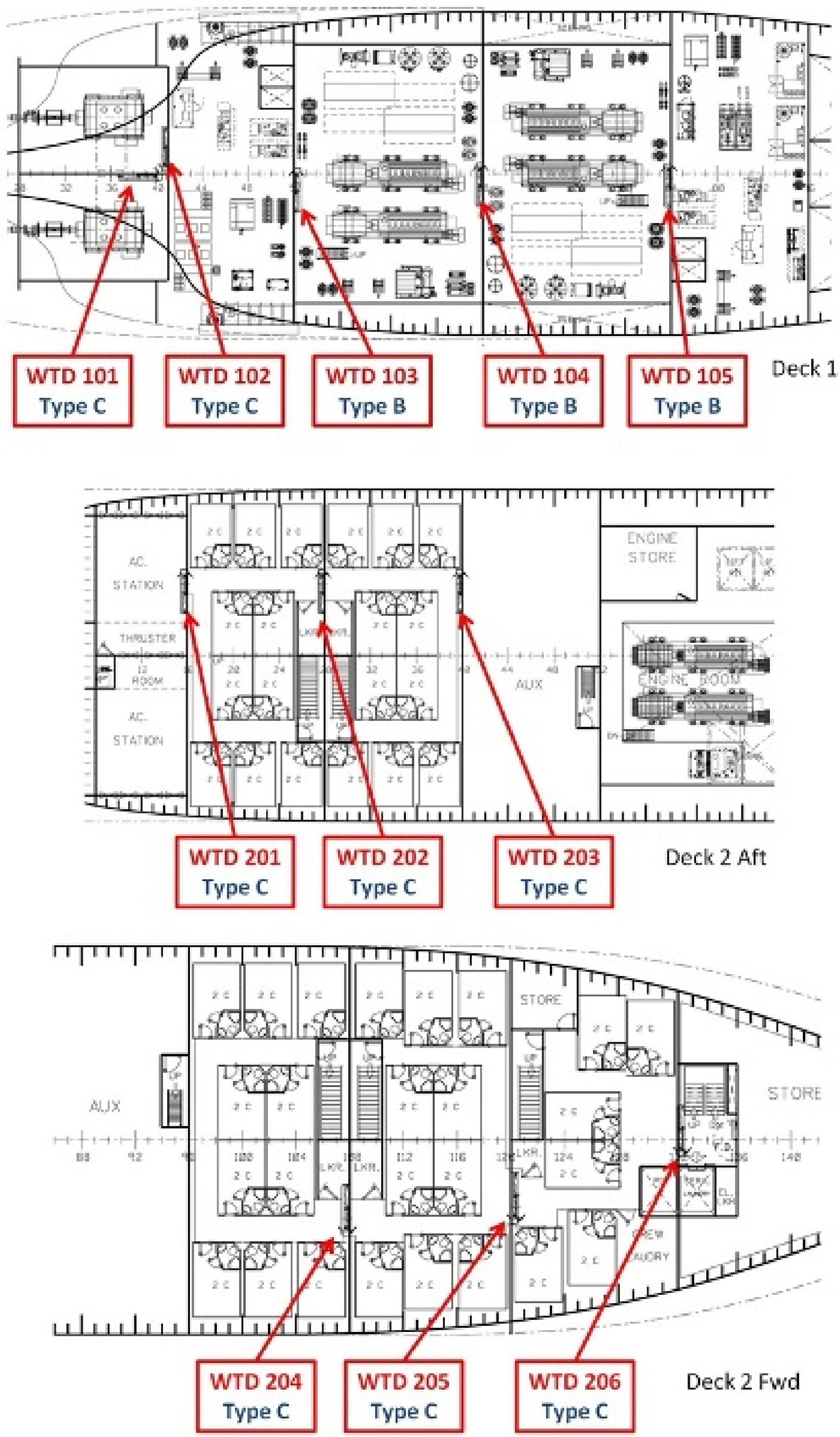

Figure 8 Ship 2 - location and category of WTD.

9.2.1.1 Investigated design variations

The initial design according to Task 1 has been calculated for information only but the design variations for current task have been investigated using as a reference the redesigned vessel for collision that correspond to vs.09 of task 1. This version has an additional watertight door on Deck 3, as shown in the Figure 9 below.

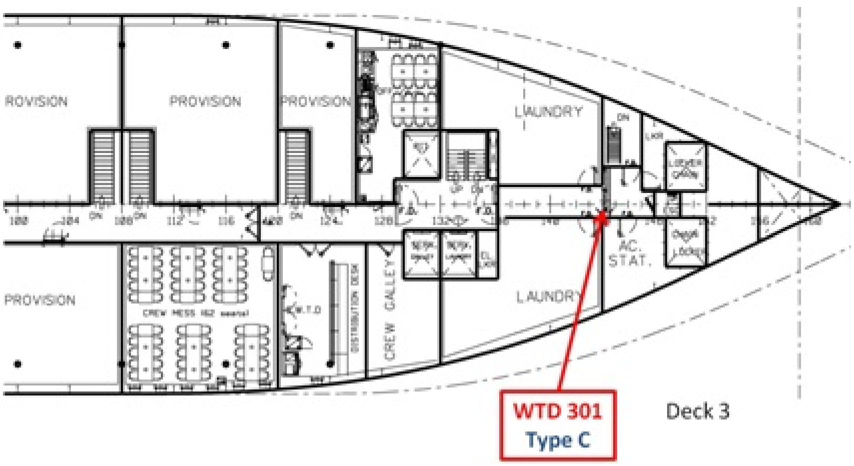

Figure 9 Ship 2 - location and category of WTD on Deck 3.

The risk control options have been studied taking into account the daily usage of each door and the effect on the general arrangement plan.

The following Table 19 shows an overview of the applied design variations, which are described in the following sections one by one in more detail.

Table 19 Ship 2- design variations.

Version	Description
00	Initial design
09	Redesigned ship (task 1)
D1	Change of door category in crew cabins area (WTD202-203-204-205-206)
D2	Deletion of door WTD105 in the machinery space by addition of a staircase on Dk1
D3	As version D2 + deletion of doors WTD103 and WTD104 by addition of a staircase from deck 1 to deck 2 and a staircase from deck 1 to deck 3. One crew cabin deleted.
D4	Combination of version D1 and D2
D5	As version D4 but door WTD105 changed from category B to category D instead of removal

9.2.1.2 Initial design version 00

The following Table 20 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version 00.

Table 20 Ship 2- Version 00, risk calculations.

Ver 00	
Initial design	
Index A (SOLAS2009)	0.7202
Volume of DAMHULL, V_{DH}	20,324
$V_{cn\ all}$	13,500
$V_{cn\ all}$ / V_{DH}	0.66424
Number of WTD	11
b	0.00699
r*	0.99536
A_{WTD}	0.71686

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.014645571	C	0.11	0.10312849
WTD102	0.068401778	C	0.11	0.10312849
WTD103	0.134797427	B	0.6	0.27990037
WTD104	0.147436745	B	0.6	0.27990037
WTD105	0.136344089	B	0.6	0.27990037
WTD201	0.067976719	C	0.11	0.10312849
WTD202	0.077963718	C	0.11	0.10312849
WTD203	0.100060914	C	0.11	0.10312849
WTD204	0.077966655	C	0.11	0.10312849
WTD205	0.078661939	C	0.11	0.10312849
WTD206	0.095744446	C	0.11	0.10312849

9.2.1.3 Redesigned ship (task 1) vs. 09

The following Table 21 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version 09.

Table 21 Ship 2- Version 09, risk calculations.

Ver 09	
Redesigned ship according to collision (task 1)	
Index A (SOLAS2009)	0.7789
Volume of DAMHULL, V_{DH}	20,428
$V_{cn\ all}$	14,593
$V_{cn\ all}$ / V_{DH}	0.71436
Number of WTD	12
b	0.00591
r*	0.99578
A_{WTD}	0.77561

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.013269223	C	0.11	0.10312849
WTD102	0.06224866	C	0.11	0.10312849
WTD103	0.122517009	B	0.6	0.27990037
WTD104	0.133805922	B	0.6	0.27990037
WTD105	0.123919571	B	0.6	0.27990037
WTD201	0.061891368	C	0.11	0.10312849
WTD202	0.070975712	C	0.11	0.10312849
WTD203	0.091101904	C	0.11	0.10312849
WTD204	0.070979513	C	0.11	0.10312849
WTD205	0.071614276	C	0.11	0.10312849
WTD206	0.087164088	C	0.11	0.10312849
WTD301	0.090512752	C	0.11	0.10312849

9.2.1.4 Version D1

In this version five watertight doors located on Deck 2 between crew cabins compartments have been changed from category C to new category D. Doors with this new category need to be closed before leaving port and they cannot be opened for passage, they are used as secondary means of escape only.

As the compartments where those doors are located are provided with vertical stairways up to deck 3, this change of category would not penalize the daily operation of the vessel.

The doors which have been transferred from category C to D are shown in below figure.

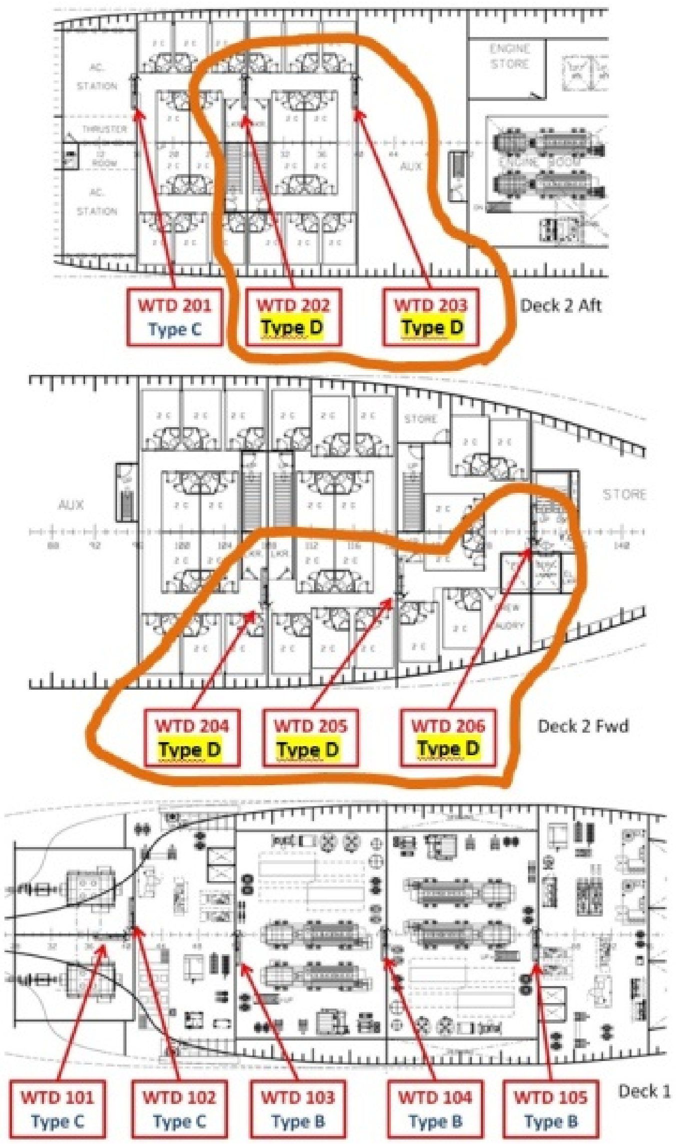

Figure 9 Ship 2 – Version D1, WTD arrangement.

For this RCO no cost are calculated as the number of WTD has not been modified and no stair cases have been added.

The following Table 59 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version D1.

Table 22 Ship 2- Version D1, risk calculations.

Ver D1	
change of door category in crew cabins area (WTD202-203-204-205-206)	
Index A (SOLAS2009)	0.7789
Volume of DAMHULL, V_{DH}	20,428
$V_{cn\ all}$	14,593
$V_{cn\ all}$ / V_{DH}	0.71436
Number of WTD	12
b	0.00554
r*	0.99604
A_{WTD}	0.77582

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.013269223	C	0.11	0.10312849
WTD102	0.06224866	C	0.11	0.10312849
WTD103	0.122517009	B	0.6	0.27990037
WTD104	0.133805922	B	0.6	0.27990037
WTD105	0.123919571	B	0.6	0.27990037
WTD201	0.061891368	C	0.11	0.10312849
WTD202	0.070975712	D	0	0
WTD203	0.091101904	D	0	0
WTD204	0.070979513	D	0	0
WTD205	0.071614276	D	0	0
WTD206	0.087164088	D	0	0
WTD301	0.090512752	C	0.11	0.10312849

9.2.1.5 Version D2

In this risk control option the door WTD105 has been removed. In order to have direct access to forward auxiliary room a staircase from deck 1 to deck 2 has been added just below the staircase already arranged on deck 2. In this way the daily access to the forward aux room will be provided by this new stairway.

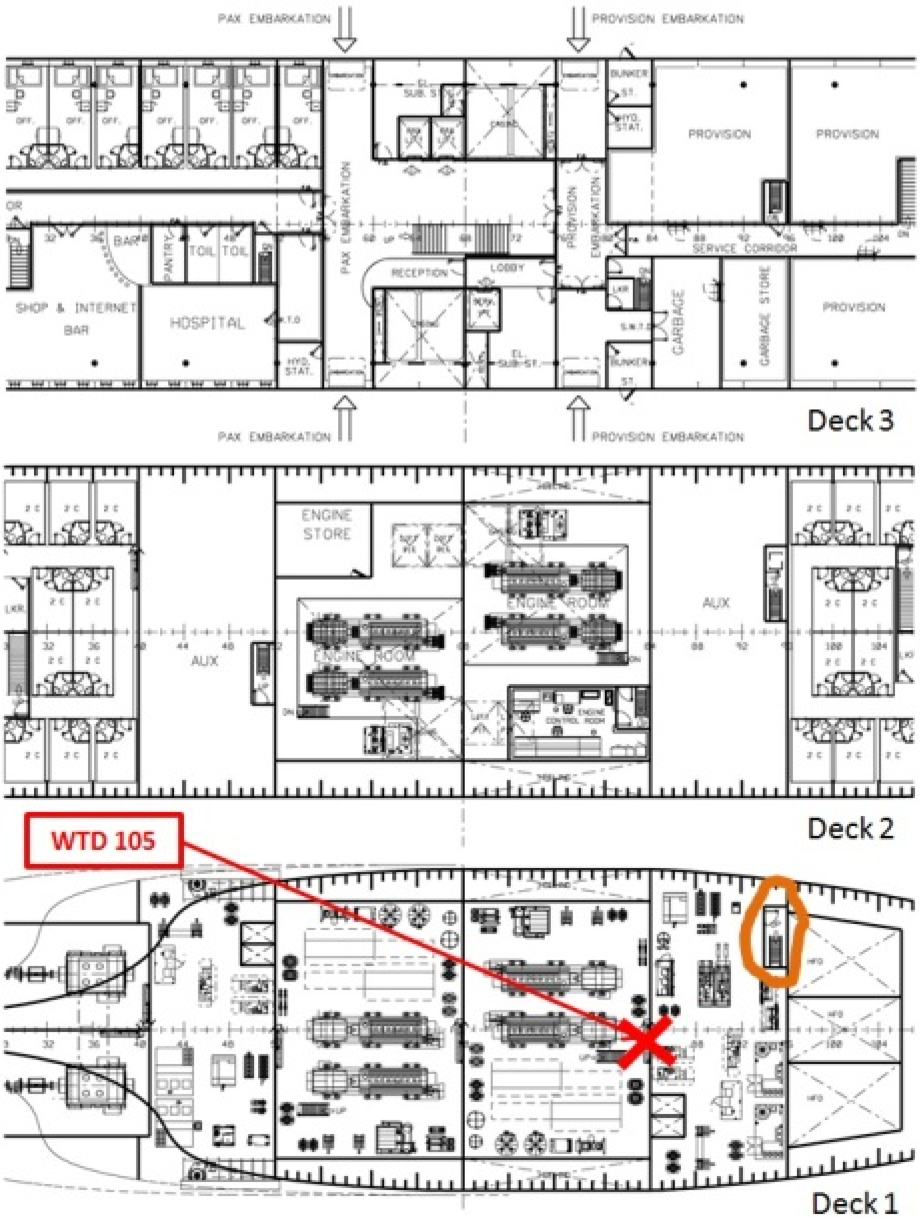

Figure 10 Ship 2- removal of door WTD105.

For this RCO the cost of the staircase addition is lower than the money saved for the removal of the WT door, and therefore, the result of the cost calculation is the following:

CAPEX	-14,418 €
OPEX	0 €
REVENUE	0 €

The following Table 23 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version D2.

Table 23 Ship 2- Version D2, risk calculations.

Ver D2	
deletion of door WTD105 in the machinery space by addition of a stair case on deck 1	
Index A (SOLAS2009)	0.7789
Volume of DAMHULL, V_{DH}	20,428
$V_{cn\ all}$	13,093
$V_{cn\ all}$ / V_{DH}	0.64093
Number of WTD	11
b	0.00455
r*	0.99708
A_{WTD}	0.77663

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.013269223	C	0.11	0.10312849
WTD102	0.06224866	C	0.11	0.10312849
WTD103	0.122517009	B	0.6	0.27990037
WTD104	0.133805922	B	0.6	0.27990037
WTD201	0.061891368	C	0.11	0.10312849
WTD202	0.070975712	C	0.11	0.10312849
WTD203	0.091101904	C	0.11	0.10312849
WTD204	0.070979513	C	0.11	0.10312849
WTD205	0.071614276	C	0.11	0.10312849
WTD206	0.087164088	C	0.11	0.10312849
WTD301	0.090512752	C	0.11	0.10312849

9.2.1.6 Version D3

This risk control option is based on version D2, with two watertight doors between engine rooms and aft aux room (WTD103 and WTD104) removed.

In order to facilitate direct access to the aft aux room a stair case from deck 1 to deck 2 has been added just below the staircase already arranged on deck 2. Moreover a new stair case from Deck 1 to Deck 4 has been added for direct access to the aft engine room. For this modification one crew cabin has been deleted to arrange the upper case on Deck 3.

Figure 11 Ship 2 – removal of WTD103 and WTD104.

For this RCO the cost for added staircases and the money saved for the removal of the WT doors have been calculated. Moreover the loss of revenue has been calculated due to removal of a pax cabin that has to be used in place of the removed crew cabin. Following the results of the cost calculation, an annual loss of income for the owner of euro Euro 50,000/year would be incurred.

CAPEX	-48,330 €
OPEX	0 €
REVENUE	-50,000 €

The following Table 61 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version D3.

Table 24 Ship 2- Version D3, risk calculations.

Ver D3	
As Vs. D2 + deletion of doors WTD103 and WTD104 by addition of a stair case on deck 1 and a staircase from deck 1 to deck 3. One crew cabin deleted	
Index A (SOLAS2009)	0.7789
Volume of DAMHULL, V_{DH}	20,428
$V_{cn\ all}$	9,573
$V_{cn\ all}$ / V_{DH}	0.46862
Number of WTD	9
b	0.00078
r*	0.99963
A_{WTD}	0.77861

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.013269223	C	0.11	0.10312849
WTD102	0.06224866	C	0.11	0.10312849
WTD201	0.061891368	C	0.11	0.10312849
WTD202	0.070975712	C	0.11	0.10312849
WTD203	0.091101904	C	0.11	0.10312849
WTD204	0.070979513	C	0.11	0.10312849
WTD205	0.071614276	C	0.11	0.10312849
WTD206	0.087164088	C	0.11	0.10312849
WTD301	0.090512752	C	0.11	0.10312849

9.2.1.7 Version D4

This version is a combination of the alternatives D1 and D2. The costs are equivalent to costs assessed for version D2 as no cost were foreseen for version D1.

Table 25 Ship 2 - Version D4, costs assessment.

CAPEX	-14,418 €
OPEX	0 €
REVENUE	0 €

The following Table 26 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version D4.

Table 26 Ship 2- Version D4, risk calculations.

Ver D4	
Combination of Vs. D1 and Vs. D2	
Index A (SOLAS2009)	0.7789
Volume of DAMHULL, V_{DH}	20,428
$V_{cn\ all}$	13,093
$V_{cn\ all}$ / V_{DH}	0.64093
Number of WTD	11
b	0.00415
r*	0.99734
A_{WTD}	0.77683

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.013269223	C	0.11	0.10312849
WTD102	0.06224866	C	0.11	0.10312849
WTD103	0.122517009	B	0.6	0.27990037
WTD104	0.133805922	B	0.6	0.27990037
WTD201	0.061891368	C	0.11	0.10312849
WTD202	0.070975712	D	0	0
WTD203	0.091101904	D	0	0
WTD204	0.070979513	D	0	0
WTD205	0.071614276	D	0	0
WTD206	0.087164088	D	0	0
WTD301	0.090512752	C	0.11	0.10312849

9.2.1.8 Version D5

This version is based on version D4 but the WT door on Deck 1 (WTD105) has been changed from category B to D instead of removal. This RCO has been calculated in order to compare the door removal with category change from the cost/effectiveness point of view.

Table 27 Ship 2- Version D5, costs assessment.

CAPEX	15,282 €
OPEX	0 €
REVENUE	0 €

The following Table 28 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version D5.

Table 28 Ship 2- Version D5, risk calculations.

Ver D5	
As. Vs. D4 but door WTD105 changed from category B to category D instead of removal	
Index A (SOLAS2009)	0.7789
Volume of DAMHULL, V_{DH}	20,428
$V_{cn\ all}$	14,593
$V_{cn\ all}$ / V_{DH}	0.71436
Number of WTD	12
b	0.00380
r*	0.99728
A_{WTD}	0.77678

ID	weighing by Vcn	category	Popen	C(t)
WTD101	0.013269223	C	0.11	0.10312849
WTD102	0.06224866	C	0.11	0.10312849
WTD103	0.122517009	B	0.6	0.27990037
WTD104	0.133805922	B	0.6	0.27990037
WTD105	0.123919571	D	0	0
WTD201	0.061891368	C	0.11	0.10312849
WTD202	0.070975712	D	0	0
WTD203	0.091101904	D	0	0
WTD204	0.070979513	D	0	0
WTD205	0.071614276	D	0	0
WTD206	0.087164088	D	0	0
WTD301	0.090512752	C	0.11	0.10312849

9.2.1.9 Comparison of results

The overview of the results is shown in the Table 29 below.

Table 29 Ship 2 – overview of results of risk calculation.

Version	Description	A_{WTD}	ΔA_{WTD} difference with respect to reference version
09	Redesigned ship (Reference version)	0.77561	0
D1	Change of door category in crew cabins area (WTD202-203-204-205-206)	0.77582	0.00021
D2	Deletion of door WTD105 in the machinery space by addition of a stairc ase on deck 1	0.77663	0.00101
D3	As Vs. D2 + deletion of doors WTD103 and WTD104 by addition of a stair case from deck1 to deck 2 and a staircase from deck 1 to deck 3. One crew cabin deleted	0.77861	0.00300
D4	Combination of Vs. D1 and Vs. D2	0.77683	0.00122
D5	As. Vs. D4 but door WTD105 changed from category B to category D instead of removal	0.77678	0.00117

The value of A_{WTD} of version D5 is very near to version D4. This result could seem strange but it is quite normal as in the parametric model the percentage of reduction for the connected volume in version D4 is not too far from the percentage of reduction for the number of WT doors. In fact, the connected volume (V_{cn}) in version D4 is about 10% lower than the value of version D5 and the number of doors in version D4 is about 8% lower than version D5.

9.2.2 Cost Benefit Assessment

The cost benefit assessment is based on the same assumptions as in task 1 for collision. Also the ∆PLL is calculated based on the risk model for collision as the parametric model is also based on the attained index for collision.

The overview of the costs for the different RCOs can be seen in the Table 30 below.

Table 30 Ship 2 – summary of cost benefit assessment.

Version	reference	D1	D2	D3	D4	D5
description	Redesigned ship (task 1)	change of door category in crew cabins area	deletion of a WT door in the fwd machinery space	As Vs. D2 + deletion of two WT doors in aft machinery rooms. One crew cabin deleted	Combination of Vs. D1 and Vs. D2	As. Vs. D4 but WT doors on DK1 changed from type B to type D
attained index A collision	0.7789	0.7789	0.7789	0.7789	0.7789	0.7789
A WTD	0.7756	0.7758	0.7766	0.7786	0.7768	0.7768
change A	0.0000	0.0002	0.0010	0.0030	0.0012	0.0012
Delta PLL	0.0000	0.0002	0.0010	0.0029	0.0012	0.0011
NetCAF = 4 Mio $	0.0000	795 $	3'911 $	11'575 $	4'689 $	4'516 $
NetCAF = 8 Mio $	0.0000	1'590 $	7'822 $	23'151 $	9'378 $	9'032 $
net Present Value NPV	**0 $**	**-135 $**	**-19'200 $**	**973'540 $**	**-19'332 $**	**18'879 $**

As shown in the above table the netCAF limits are small as the DPLL are very low. With this figure it's not possible to have a RCO cost effective when one or more cabins have been removed and the loss of income is calculated subsequently (e.g. version D3). Even the limited cost for the addition of stair cases only, without cabin removal (e.g. version D5), could result in a RCO not cost effective due to limited increase of A index and therefore very low netCAF limit; in this situation a reduction of the cost is obtained when some WT door is removed (e.g. version D2 and D4).

9.2.2.1 Summary

Due to limited number of WT doors the increase of risk due to watertight doors is not so high on this vessel. In any case, it is possible to generate RCOs that stay within the limits for cost effectiveness even if they are very low. Good results may be obtained by the removal of some WTD that can be compensated by a stair case addition for direct access from bulkhead deck to the below compartment but attention should be paid to avoid cabins loss in the location where the stair cases are to be added. Moreover the use of the new category D, which is a door that may only be used in case of emergency as secondary means of escape, may be useful in particular in the crew cabins compartment where the stairways for normal access to those compartments are already provided.

9.3 Ship #3 Baltic cruise ferry

9.3.1 Location of WTD

The reference design of Baltic Cruise Ferry has in total 11 watertight doors, as listed in Table 31 and shown in Figure 12 and Figure 13. It reflects a typical design of modern RoPax ship, where access to different spaces along ship's length through watertight doors below car deck is provided. The watertight doors aft of the Main Engine Rooms are located on deck 2. Access to LNG space, Forward Pump Room and Sewage+RO Rooms are located on Tank Top level. Passage into Forward Pump Room and Bow Thruster Room is provided via provision area located on deck 2.

Above the car deck on deck 3 one watertight door is located in front of service lift, which should be closed before the voyage commences and shall be kept closed while at sea. Depending on the purpose the door categories are defined together with the operator.
All doors below bulkhead deck are of category C and this one WT door above car deck is category D. It is to be noted that all doors are category C doors meaning that they are only opened to permit the passage of crew and are closed immediately once the transit through the door is complete.

However, in this study also WT door above car deck was assumed to be C category.

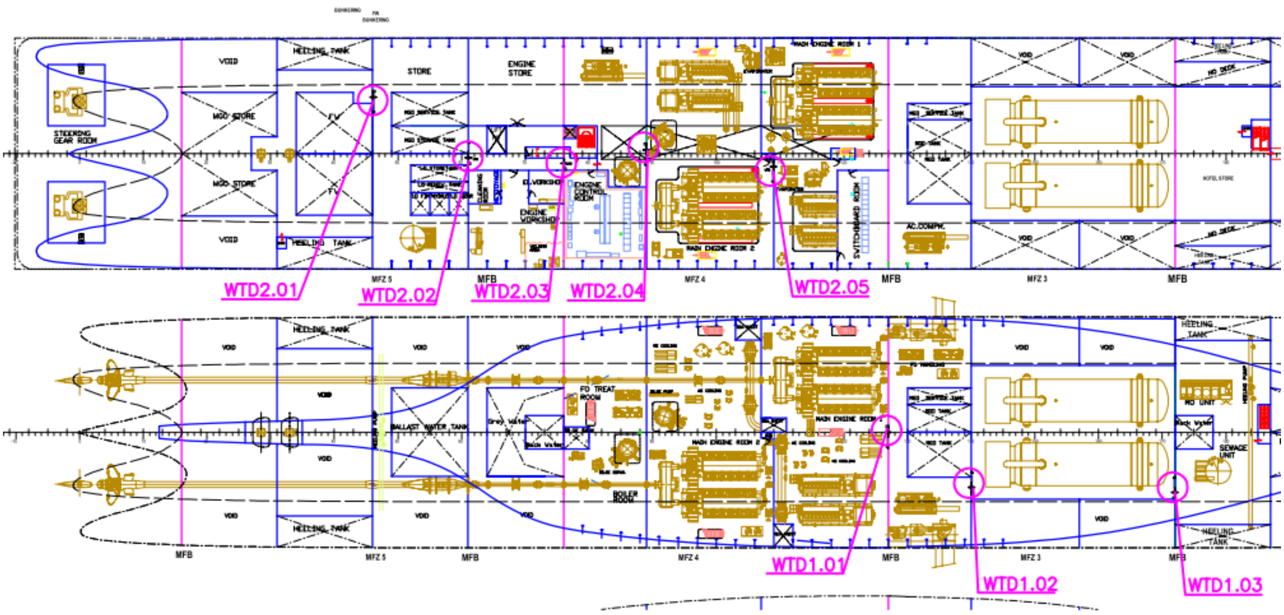

Figure 12 Ship 3 – Version A, location of WTD in the aft part.

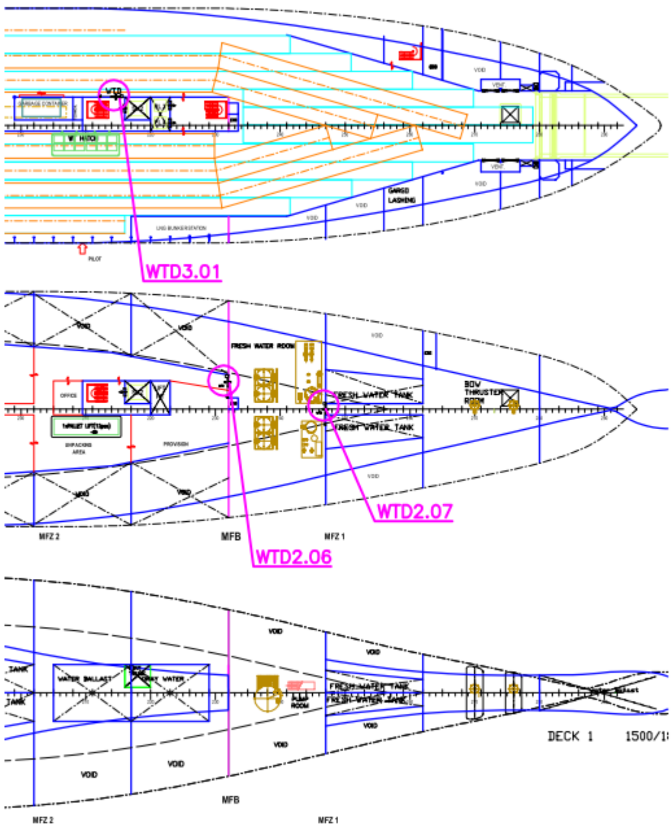

Figure 13 Ship 3 - Version A, location of WTD in the forward part.

Table 31 Ship 3 - list of WTD.

ID	FRAME	X	Y	Z	Category
WTD1.01	127	101.60 m	0.00 m	2.80 m	C
WTD1.02	140	112.00 m	8.10 m	2.50 m	C
WTD1.03	172	137.60 m	8.10 m	2.50 m	C
WTD2.01	46	36.80 m	7.70 m	6.55 m	C
WTD2.02	61	48.80 m	1.12 m	6.55 m	C
WTD2.03	76	60.80 m	1.80 m	6.55 m	C
WTD2.04	89	71.20 m	0.00 m	6.55 m	C
WTD2.05	109	87.20 m	2.20 m	6.55 m	C
WTD2.06	232	185.60 m	2.75 m	6.55 m	C
WTD2.07	247	197.60 m	0.70 m	6.55 m	C
WTD3.01	215	172.00 m	3.50 m	9.90 m	D *

*In calculations assumed C

9.3.1.1 Investigated design variations

As already mentioned above, the considerations of risk control options are driven by the factors which influence the overall risk contribution due to WTDs. Viable options for control of risk comprise removal of watertight doors, minimisation of the volume connected by WTDs, or minimisation of the frequency that any door is used while at sea.

Co-operation with the operator has shown that there is no need to keep watertight doors open due to operational reasons. So category C for all WT doors will not cause any problems in practise.

Therefore, there is no option to minimize the frequency of a certain door usage while at sea.

The most important and most reasonable option is to optimize access along whole ship's length located on deck 2. Secondly it should be important to separate passage from aft to forward from LNG space below bulkhead deck.

The following table shows an overview of the applied design variations, which will be described in the following sections one by one in more detail.

Table 32 Ship 3 - design variations.

Version	Description
A	Reference version
B	Two WT doors changed into deck 2 No WT doors deleted
C	As B version + 2 WT doors deleted in forward part

9.3.1.2 Version A

The following Table 33 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version A.

Table 33 Ship 3- Version A, risk calculations.

Ver A	
Reference Version	
Index A (SLF55)	0.83260
Volume of DAMHULL, V_{DH}	88,379
$V_{cn\ all}$	49,587
$V_{cn\ all}$ / V_{DH}	0.56107
Number of WTD	11
b	0.01134
r*	0.99364
A_{WTD}	0.82730

ID	Vcn/VDH	category	Popen	C(t)
WTD1.01	0.066628676	C	0.11	0.10312849
WTD1.02	0.065480949	C	0.11	0.10312849
WTD1.03	0.073174115	C	0.11	0.10312849
WTD2.01	0.025682964	C	0.11	0.10312849
WTD2.02	0.018254277	C	0.11	0.10312849
WTD2.03	0.003890822	C	0.11	0.10312849
WTD2.04	0.060666358	C	0.11	0.10312849
WTD2.05	0.058403299	C	0.11	0.10312849
WTD2.06	0.024821141	C	0.11	0.10312849
WTD2.07	0.027568932	C	0.11	0.10312849
WTD3.01	0.575428466	C	0.11	0.10312849

9.3.1.3 Version B

Version B is shown Figure 15. None watertight doors, listed in Table 34, have been removed in this version. To fulfil requirement to keep access along ship's length on deck 2 and to separate passage from LNG space two watertight doors has been lifted from Tank Top into deck 2 level.

The following changes in spaces have been done in version B;

Change 1

The door WTD1.01 at frame 127 and the door WTD1.03 at frame 172 have been lifted into deck 2 and renumbered accordingly WTD2.06 and WTD2.07.

Access to LNG space is still located on Tank Top level. It is easy to go down from deck 2 at frame 128 and separately to go to the LNG space. Exit from this space has been relocated into forward at frame 171.

Change 2 and 3

MGO Tank SB has been moved 1.4 m more to starboard side to allow passage in the middle of the tanks. The watertight passage through LNG space has been done just below car deck between the LNG tanks. Section of the corridor is shown in Figure 24. This corridor between frames 149-172 is open to aft watertight compartment between frames 127-140.

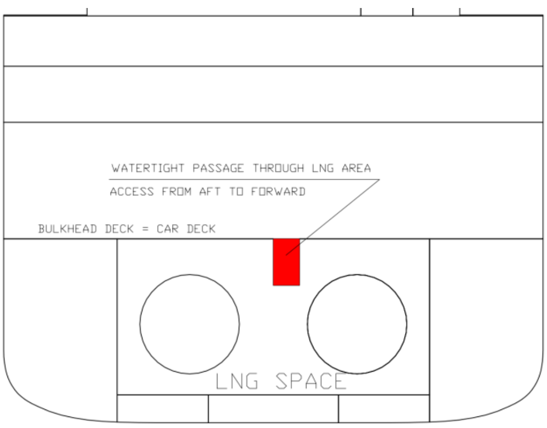

Figure 14 Ship 3 - Separated watertight passage through LNG space.

Change 4 and 5

The reference version has watertight deck area on deck 2 between frames 172-187. The watertight deck is removed and stairs into below machinery space has been changed into aftward of the compartment. Hotel store has been divided due to the extended service corridor up to frame 172. By this way access between aft machinery spaces and Forward Pump Room and Bow Thruster Room is possible. This alternative will give also safety in case of fire above the car deck.

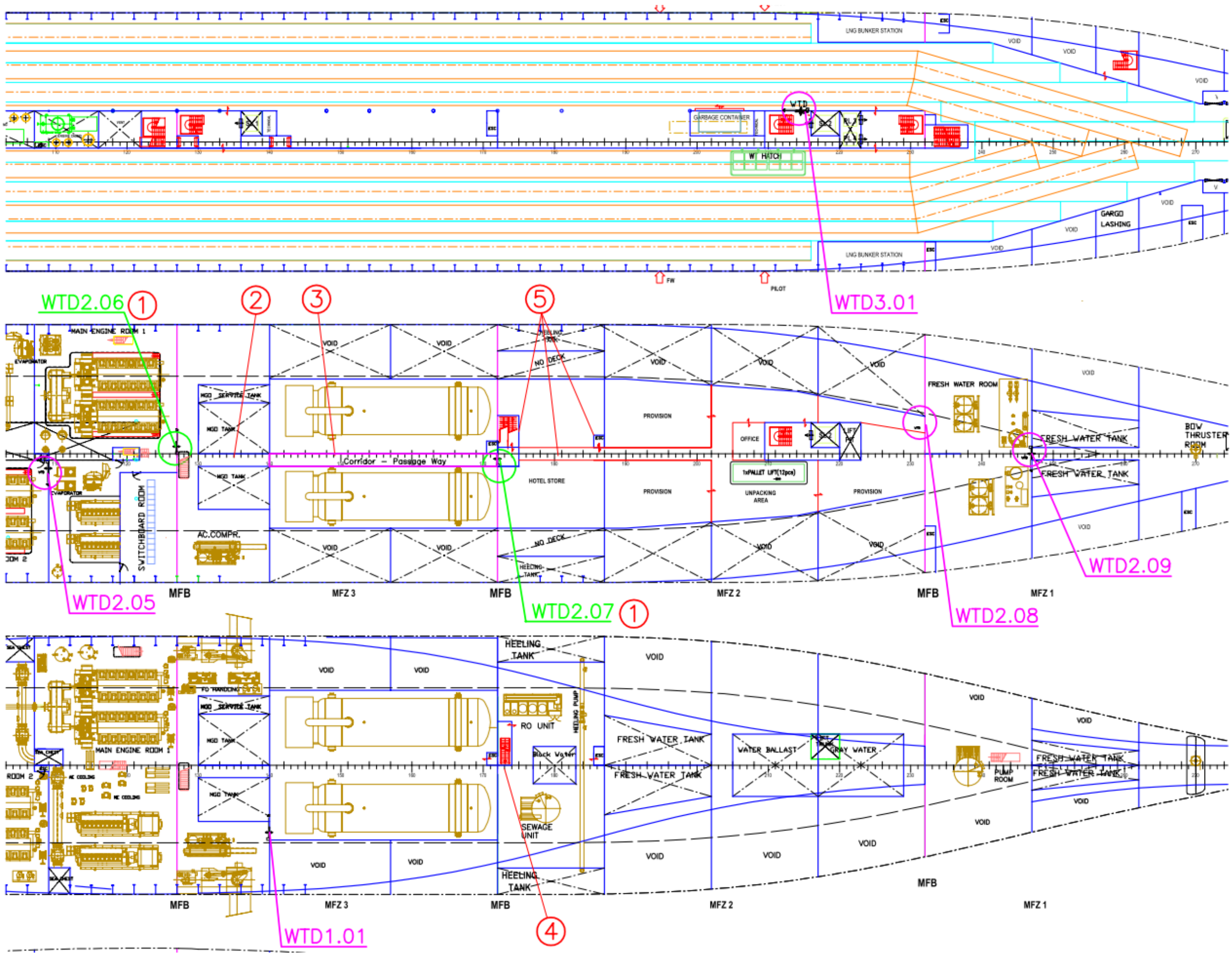

Figure 15 Ship 3 – Version B, WTD arrangement.

Table 34 Ship 3- Version B, list of WTDs.

ID	FRAME	X	Y	Z
WTD1.01	140	112.00 m	8.10 m	2.50 m
WTD2.01	46	36.80 m	7.70 m	6.55 m
WTD2.02	61	48.80 m	1.12 m	6.55 m
WTD2.03	76	60.80 m	1.80 m	6.55 m
WTD2.04	89	71.20 m	0.00 m	6.55 m
WTD2.05	109	87.20 m	2.20 m	6.55 m
WTD2.06	127	101.60 m	1.00 m	6.55 m
WTD2.07	127	137.60 m	1.00 m	7.40 m
WTD2.08	232	185.60 m	2.75 m	6.55 m
WTD2.09	247	197.60 m	0.70 m	6.55 m
WTD3.01	215	172.00 m	3.50 m	9.90 m

The consequence for such changes (1-5) listed above result to the costs as shown in Table 35.

Table 35 Ship 3- Version B, cost assessment.

Exchange rate 1 € is 1 ,35 $

Total Costs for Investment			CAPEX	135,594 $
Total Change of operational costs			OPEX	0 $
Total Change of annual revenue			REVENUE	0 $

Calculation of investment costs				
	size	Unit	spec value	costs
Costs for financing, insurance etc	125,550 $	$	8%	10,044 $
add steel, passage way	25	t	6,000 €	202,500 $
Deleted stairs	15	m2	-2,500 €	-50,625 $
Deleted hotel stores	13	m2	-1,500 €	-26,325 $

The effect on operational procedures is ignored. Stairs on deck 3 and 4 from Hotel Store have been deleted. Biggest cost is due to the addition in steel weight.

The following Table 36 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version B.

Table 36 Ship 3- Version B, risk calculations.

Ver B				
Two WT doors moved into 2.deck				
Index A (SLF55)	0.83136			
Volume of DAMHULL, V_{DH}	88,379			
$V_{cn\ all}$	49,282			
$V_{cn\ all}$ / V_{DH}	0.55762			
Number of WTD	11			
b	0.01134			
r*	0.99367			
A_{WTD}	0.82610			
ID	Vcn/VDH	category	Popen	C(t)
WTD1.01	0.06710106	C	0.11	0.10312849
WTD2.01	0.02724872	C	0.11	0.10312849
WTD2.02	0.01936715	C	0.11	0.10312849
WTD2.03	0.00412803	C	0.11	0.10312849
WTD2.04	0.06436488	C	0.11	0.10312849
WTD2.05	0.06196385	C	0.11	0.10312849
WTD2.06	0.06551074	C	0.11	0.10312849
WTD2.07	0.01909327	C	0.11	0.10312849
WTD2.08	0.02742603	C	0.11	0.10312849
WTD2.09	0.02924967	C	0.11	0.10312849
WTD3.01	0.61454659	c	0.11	0.10312849

9.3.1.4 Version C

This version is based on version B, except two watertight doors in forward part has been removed, please see Table 37 and Figure 16. Access door below bulkhead deck has been removed from aft machinery spaces into Forward Pump Room and into Bow Thruster Room. The operator has informed that the only possible watertight doors, which could be removed, are these doors located forward of the stores.

The following changes in general arrangement has been done in version C;

Changes 1-4

Changes 1-4 are same as in version B.

Changes 5, 6

Due to restricted access longitudinally there is no need to extend service corridor in hotel store. Hotel store will be like in the reference version.

Change 7

Watertight doors WTD2.08 at frame 232 and WTD2.09 at frame 247 has been deleted.

Change 8

An access to Forward Pump Room and to Bow Thruster Room has to be rebuilt from above deck 4.

Therefore additional staircases to be provided from deck 2 into deck 4.

Capacity of Fresh Water Tanks will be increased due to deletion of corridor in the middle of the tanks.

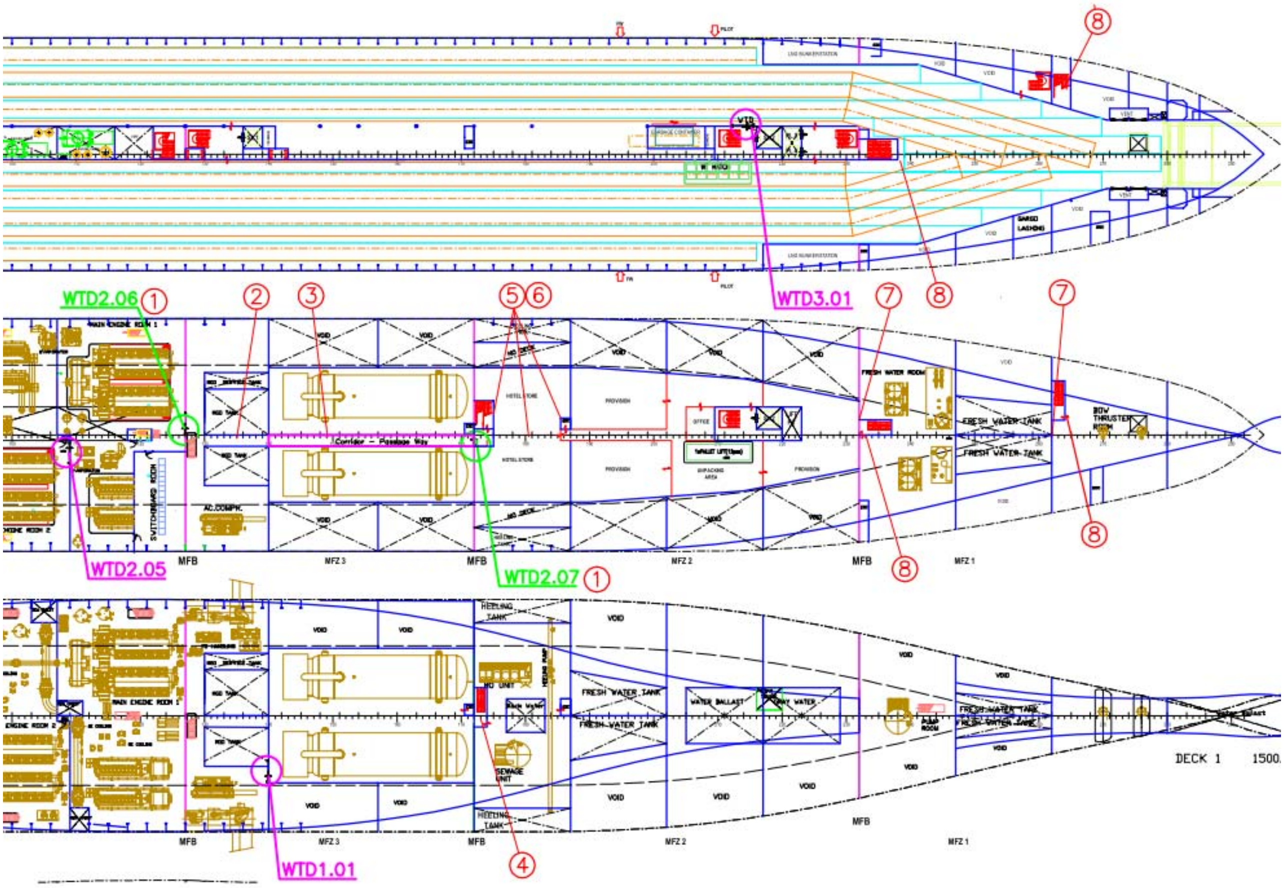

Figure 16 Ship 3 – Version C, WTD arrangement.

Table 37 Ship 3- Version C, list of WTDs.

ID	FRAME	X	Y	Z
WTD1.01	140	112.00 m	8.10 m	2.50 m
WTD2.01	46	36.80 m	7.70 m	6.55 m
WTD2.02	61	48.80 m	1.12 m	6.55 m
WTD2.03	76	60.80 m	1.80 m	6.55 m
WTD2.04	89	71.20 m	0.00 m	6.55 m
WTD2.05	109	87.20 m	2.20 m	6.55 m
WTD2.06	127	101.60 m	1.00 m	6.55 m
WTD2.07	127	137.60 m	1.00 m	7.40 m
WTD3.01	215	172.00 m	3.50 m	9.90 m

The consequence for such changes (1-8) listed above result to costs as summarised in Table 39.

Table 38 Ship 3- Version C, cost assessment.

Exchange rate 1 € is 1 ,35 $

Total Costs for Investment			CAPEX	275,562 $
Total Change of operational costs			OPEX	0 $
Total Change of annual revenue			REVENUE	-80,798 $

Calculation of investment costs				
	size	Unit	spec value	costs
Costs for financing, insurance etc	255,150 $	$	8%	20,412 $
added steel, passage way, added stairs	35	t	6,000 €	283,500 $
Deleted and added stairs	20	m2	2,500 €	67,500 $
Deleted technical area	14	m2	-1,500 €	-28,350 $
Deleted 2 pcs watertight doors	2	pcs	-25,000 €	-67,500 $

Calculation of revenue				
	size	Unit	spec value	costs
lose of lane meter due to added stair	5	m	-11,970 €	-80,798 $

It is assumed that changes in operational procedures are marginal, and therefore, they have been ignored. The removal of the two watertight doors would decrease costs. Biggest cost is due to the addition in steel weight. Because there is no watertight door in option C into forward Pump room, it is necessary to build additional staircases from Pump Room into deck 5 through car deck thus losing lane meters.

The following Table 39 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version C.

Table 39 Ship 3- Version C, risk calculations.

Ver C				
Delete WTD doors				
Index A (SLF55)	0.83178			
Volume of DAMHULL, V_{DH}	88,379			
$V_{cn\ all}$	47,330			
$V_{cn\ all}$ / V_{DH}	0.53553			
Number of WTD	9			
b	0.01134			
r*	0.99392			
A_{WTD}	0.82672			
ID	Vcn/VDH	category	Popen	C(t)
WTD1.01	0.070715989	C	0.11	0.10312849
WTD2.01	0.028716692	C	0.11	0.10312849
WTD2.02	0.020410512	C	0.11	0.10312849
WTD2.03	0.004350415	C	0.11	0.10312849
WTD2.04	0.067832399	C	0.11	0.10312849
WTD2.05	0.065302023	C	0.11	0.10312849
WTD2.06	0.069039996	C	0.11	0.10312849
WTD2.07	0.027033991	C	0.11	0.10312849
WTD3.01	0.646597985	C	0.11	0.10312849

9.3.1.5 Comparison of results

The overview of the results is shown in the Table 40 below.

Table 40 Ship 3 – overview of results of risk calculation.

Version	Description	A_{SLF55}	ΔA* collision	A_{WTD}	Change A_{SLF55}-A_{WTD}	ΔA*
A	Reference version	0.83260	0	0.82730	-	0
B	Two WT doors changed into deck 2 No WT doors deleted	0.83136	-0.00124	0.82610	-0.00526	-0.00650
C	As B version + 2 WT doors deleted in forward part	0.83178	-0.00082	0.82672	-0.00506	-0.00588

To optimize the use of the watertight doors and to find out most optimum passage into all spaces along ship's length some changes in internal subdivision has been made. Therefore it was necessary first to calculate the attained index according to SLF55 for version B and C. Because the A_{SLF55} differs from basic value, it seems to be more correct to add the change between A_{SLF55}-A_{WTD} separately in both versions into the change of the attained index due to collision.

The explanations regarding the impact of removal of watertight doors are reflected in observations made in chapter 9.1.3.

9.3.2 Cost Benefit Assessment

The cost benefit assessment is based on the same assumptions as in task 1 for collision. Also the ΔPLL is calculated based on the risk model for collision as the parametric model is also based on the attained index for collision.

The overview of the costs for the different RCOs can be seen in the Table 41 below.

Table 41 Ship 3 – summary of cost benefit assessment.

Version ->	A	B	C
Description	Reference version	Two WT doors changed into d. 2 No WT doors removed	As B version + 2 WT doors deleted in forward part
Attained index A Collision SLF55	0.83260	0.83136	0.83178
A_{WTD}	0.82730	0.82610	0.82672
ΔA	-	-0.00650	-0.00588
ΔPLL	0.0000	0.1257	0.1137
NetCAF = 4 Mio $	0 $	502,657 $	454,711 $
NetCAF = 8 Mio $	0 $	1,005,313 $	908,649 $
Net Present Value NPV	0 $	141,182 $	2,538,184 $

It be seen that the removal of the watertight doors has a big impact on space and will result in a loss of lane meters. Access to forward machinery spaces is only from deck 4, which will make worse operation in practise. The loss of revenue due to the loss of lane meters immediately leads to high costs which are beyond the netCAF limits.

The netCAF limits are relatively small due to the small ΔPLL based on the small change of A.

9.3.2.1 Summary

The ship is a design with a small number of WTD with respect to its size. Therefore, any scope for reduction of risk due to WTD is limited. However, the investigation of different RCOs based on the parametric model has shown that there are ways to minimize the risk due to watertight doors. In this sample ship following actions seems to reduce the risk due to watertight doors by keeping in mind that all doors are category C doors, doors only opened to permit the passage of crew and are closed immediately once the transit through the door is complete;

1. Minimize as far as possible number of watertight doors on Tank Top level.
2. Arrange an access within ship's length below bulkhead deck, on upper deck level.
3. Arrange separate watertight passage through LNG space.
4. Removal of forward located watertight doors will not have as big reduction of the risk due to watertight doors as it was expected.

Due to the change of the internal subdivision a combined effect due to the change of WTD and the attained index could be seen. This needs to be further studied in task 4 of the project.

9.4 Ship #4 Mediterranean RoPax

9.4.1 Location of WTD

This reference design of this ship has in total 16 watertight doors.

Most of the doors are the second mean of escape, where in the watertight compartment only one enclosed staircase or vertical ladder is provided.

Other doors are needed to allow the transportation of goods during daily operation, like in the lower hold between the lift and the provision rooms, or they are used for maintenance and transport of spare parts like in the engine room.

The service lift at the fore part of the lower hold does not deserve the car deck 3

Depending on the purpose the door categories are defined together with the operator.

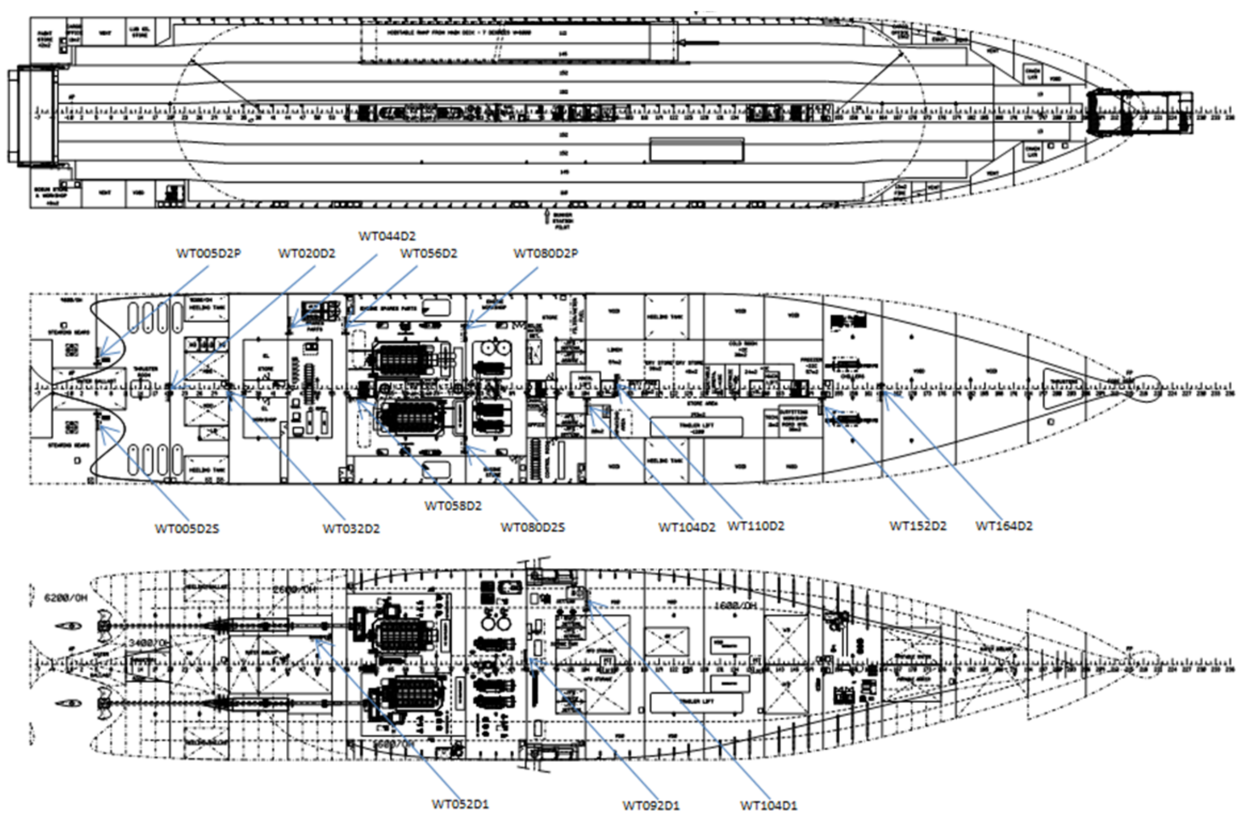

Figure 17 Ship 4, location of WTD.

Two doors have been considered in category B in order to facilitate the daily circulation from engine room to engine workshop and from the service lift to the provision lower hold:

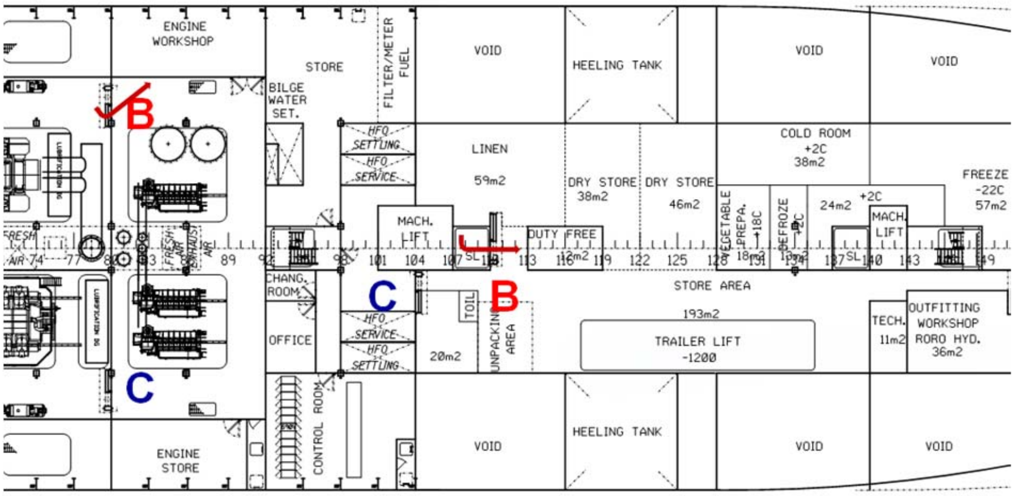

Table 42 Ship 4, list of WTD.

ID	Deck	Type
WT052D1	Deck 1	C
WT092D1	Deck 1	C
WT104D1	Deck 1	C
WT005D2P	Deck 2	C
WT005D2S	Deck 2	C
WT020D2	Deck 2	C
WT032D2	Deck 2	C
WT044D2	Deck 2	C
WT056D2	Deck 2	C
WT058D2	Deck 2	C
WT080D2P	Deck 2	B
WT080D2S	Deck 2	C
WT104D2	Deck 2	C
WT110D2	Deck 2	B
WT152D2	Deck 2	C
WT164D2	Deck 2	C

9.4.2 Calculation of risk from watertight doors

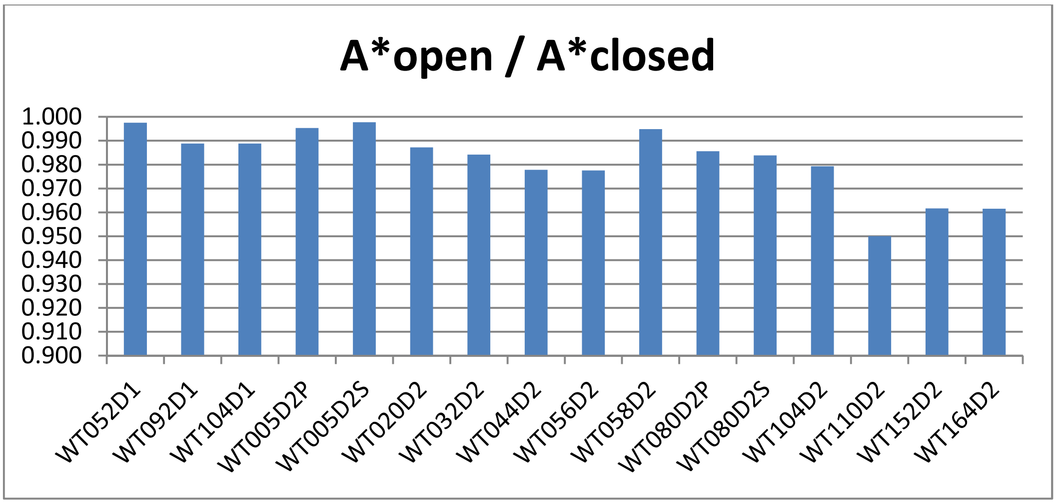

Figure 18 Ship 4, impact of watertight doors.

The following Table 43 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on version C.

Table 43 Ship 4- risk calculations.

ID	Type	Popen	C(t)	weighing by Vcni	bi
WT052D1	C	0.11	0.103	0.032726	0.000371
WT092D1	C	0.11	0.103	0.054129	0.000614
WT104D1	C	0.11	0.103	0.039113	0.000444
WT005D2P	C	0.11	0.103	0.022381	0.000254
WT005D2S	C	0.11	0.103	0.022381	0.000254
WT020D2	C	0.11	0.103	0.022100	0.000251
WT032D2	C	0.11	0.103	0.036417	0.000413
WT044D2	C	0.11	0.103	0.040668	0.000461
WT056D2	C	0.11	0.103	0.041824	0.000474
WT058D2	C	0.11	0.103	0.063156	0.000716
WT080D2P	B	0.6	0.280	0.063804	0.010715
WT080D2S	C	0.11	0.103	0.062346	0.000707
WT104D2	C	0.11	0.103	0.050049	0.000568
WT110D2	B	0.6	0.280	0.363580	0.061060
WT152D2	C	0.11	0.103	0.050315	0.000571
WT164D2	C	0.11	0.103	0.035011	0.000397
				b =	0.0782708
				r* = A*op/A*closed =	0.94904861

9.4.3 Summary

With the assumptions and method described in the chapter “risk method”, the reduction of index due to the watertight doors is r* = 0.949.

It is to be noted that this factor increases up to 0.99 if the B-doors are changed in C-doors.

9.5 Ship #5 Small RoPax

9.5.1 Location of Watertight Doors

The reference design of Ship 5 has a total of 4 watertight doors, please see Table 44 and Figure 19. In this design the watertight doors are used as the second means of escape from watertight compartments below the bulkhead deck as well as providing a route between the machinery spaces during daily operations and maintenance, e.g. the movement of spare parts. There are no watertight doors above the vehicle deck. On advice from the operator the doors have been categorised as shown in Figure 19.

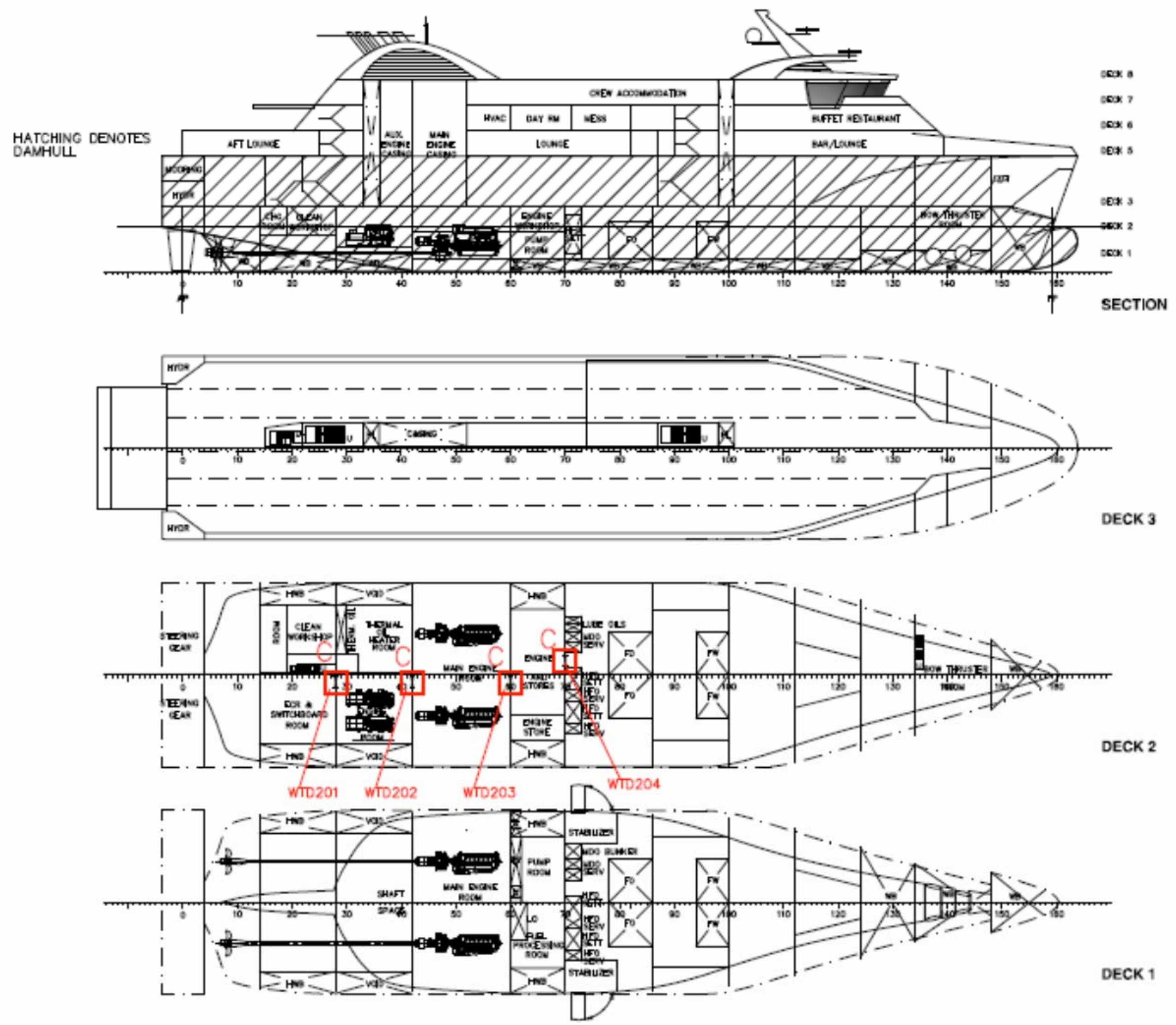

Figure 19 Ship 5 - location of WTD.

Table 44 Ship 5 - List of WTD.

ID	Deck	category
WTD201	2	C
WTD202	2	C
WTD203	2	C
WTD204	2	C

Please note that all doors are category C doors meaning that they are only opened to permit the passage of crew and are closed immediately once the transit through the door is complete.

9.5.2 Investigated design variations

The initial design developed in Task 1 has been assessed but the design variations for this task have been investigated using as a reference the vessel selected from the redesign process in Task 1 for collision, i.e. RCO1. This reference version is referred to as M21 in this assessment.

As mentioned earlier, the considerations of risk control options are driven by the factors which influence the overall risk contribution due to WTDs. Viable options for control of risk comprise removal of watertight doors, minimisation of the volume connected by WTDs, or minimisation of the frequency that any door is used while at sea.

As part of the Task 1 investigations it was found that further sub-dividing the current design failed to produce an enhanced stability standard whilst still meeting the demands for space, minimum damage length, escape routes, etc., and therefore on the same basis options for reducing the individual volumes of the compartments connected by watertight doors was not pursued as a suitable design variation.

The reference vessel has been designed such that in accordance with the requirements of SOLAS Chapter II-1, reg 17-1 1.1. all accesses that lead to below the bulkhead deck must be from a minimum of 2.5m above the bulkhead deck. Therefore, any access between adjacent watertight compartments not via watertight doors must involve going up to this +2.5m level, along and then back down.

The following Table 45 shows an overview of the applied design variations, which will be described in the following sections one by one in more detail.

Table 45 Ship 5 - design variations.

Version	Description
Initial Design	Initial Design
M21	Reference version (RCO1 from Task 1)
M21_1	Removal of WTD204
M21_2	Assigning new door categories

9.5.2.1 Initial Design

The following Table 46 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on the initial design version.

Table 46 Ship 3- Version Initial Design, risk calculations.

Initial Design	
Index A (SOLAS2009)	0.7947
Volume of DAMHULL, V_{DH}	19,237
$V_{cn\ all}$	3,705
$V_{cn\ all}$ / V_{DH}	0.19260
Number of WTD	4
b	0.01134
r*	0.99782
A_{WTD}	0.79296

ID	Weighing by Vcn	category	Popen	C(t)
WTD201	0.191150945	C	0.11	0.10312849
WTD202	0.298567995	C	0.11	0.10312849
WTD203	0.290089459	C	0.11	0.10312849
WTD204	0.220191602	C	0.11	0.10312849

9.5.2.2 Version M21

The following Table 47 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on the version M21.

Table 47 Ship 3- Version M21, risk calculations.

Ver M21	
Reference Version	
Index A (SOLAS2009)	0.84257
Volume of DAMHULL, V_{DH}	19,868
$V_{cn\ all}$	3,932
$V_{cn\ all}$ / V_{DH}	0.19791
Number of WTD	4
b	0.01134
r*	0.99775
A_{WTD}	0.84068

ID	Weighing by Vcn	category	Popen	C(t)
WTD201	0.192410046	C	0.11	0.10312849
WTD202	0.298039524	C	0.11	0.10312849
WTD203	0.288323754	C	0.11	0.10312849
WTD204	0.221226675	C	0.11	0.10312849

9.5.2.3 Version M21_1

The Engine Control Room is located on Deck 2 aft of the Auxiliary Engine Room. It was considered that a direct route below the bulkhead deck between this location and the Main Engine Room (via doors WTD201 & WTD202) was vital to the daily operation of the vessel. Similarly the Engine Workshop and Store is located forward of the Main Engine Room and again a direct link, via WTD203, was considered vital. Whilst door WTD204 links machinery spaces it is considered the least vital of the WTDs and therefore for the purposes of this analysis has been removed from the design.

Given that the reference design assumes the watertight door as the secondary means of escape, the impact of removing it would be that an additional access from 2.5m above the bulkhead deck would be required for the watertight compartment forward of the door. Whilst a detailed design solution has not been developed it is considered that the internal re-arrangement of the compartment and the centre casing would allow for an achievable solution. Estimated costs for such a change are summarised in Table 48.

Table 48 Ship 5- Version M21_1, cost assessment.

Total Costs for Investment			CAPEX	-17,496 $
Total Change of operational costs			OPEX	0 $
Total Change of annual revenue			REVENUE	0 $

Calculation of investment costs				
	size	Unit	spec value	costs
Costs for financing, insurance etc	-16,200 $	$	8%	-1,296 $
Additional Steel Staircase	1		8,100	8,100 $
Deleted Watertight Door	1		-24,300	-24,300 $

The following Table 49 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on the version M21_1.

Table 49 Ship 5 - Version M21_1, risk calculations.

Ver M21_1	
Removed Door WTD204	
Index A (SOLAS2009)	0.84257
Volume of DAMHULL, V_{DH}	19,868
$V_{cn\ all}$	3,053
$V_{cn\ all}$ / V_{DH}	0.15366
Number of WTD	3
b	0.00883
r*	0.99864
A_{WTD}	0.84143

ID	Weighing by Vcn	category	Popen	C(t)
WTD201	0.192410046	C	0.11	0.10312849
WTD202	0.298039524	C	0.11	0.10312849
WTD203	0.288323754	C	0.11	0.10312849

9.5.2.4 Version M21_2

This version considered changing the categorisation of WTD204 from category C to an equivalent category D. However, in this scenario it is proposed that the door would still meet the technical requirements in SOLAS regulations II-1/13.5.1 to 13.5.3 and 13.6, which also includes the requirements in paragraph 7 of SOLAS regulation II-1/13, and could still be used as an escape in the event of an emergency but could not be utilised in the ordinary operation of the vessel. This change may require some additional methods of identifying the door and monitoring it as such and training of the crew to ensure that the door is not used inappropriately but for the purposes of this assessment it has been assumed that there is no cost impact of this change.

The following Table 50 summarises risk calculations according to the risk method described in chapter 8, for assessing impact of doors on the version M21_2.

Table 50 Ship 5 - Version M21_2, risk calculations.

Ver M21_2	
Change to category D WTD204	
Index A (SOLAS2009)	0.84257
Volume of DAMHULL, V_{DH}	19,868
$V_{cn\ all}$	3,932
$V_{cn\ all} / V_{DH}$	0.19791
Number of WTD	4
b	0.00883
r*	0.99825
A_{WTD}	0.84110

ID	weighing by Vcn	category	Popen	C(t)
WTD201	0.192410046	C	0.11	0.10312849
WTD202	0.298039524	C	0.11	0.10312849
WTD203	0.288323754	C	0.11	0.10312849
WTD204	0.221226675	D	0	0

9.5.2.5 Comparison of Results

The overview of the results is shown in the following table.

Table 51 Ship 5 – overview of results of risk calculation.

Version	Description	A SOLAS2009	A_{WTD}	ΔA_{WTD} difference with respect to reference version
Initial	Initial Design	0.7947	0.7930	
M21	Reference version	0.8426	0.8407	0.0000
M21_1	Removal of WTD	0.8426	0.8414	0.0007
M21_1	Assigning new door category	0.8426	0.8411	0.0004

The analysis shows that for the reference design the effect of considering the WTDs is a relatively small reduction in A of 0.002 (0.2%). This can be attributed to the relatively small number of watertight doors, the fact that they are all category C doors, with the associated small probability of the door being opened at any given time, and also to the ratio of the connected volumes to the overall volume, DAMHULL, considered in the analysis. For this design the vehicle deck, as the bulkhead deck, is considered watertight and it is included in the DAMHULL volume. However, it is not connected to below decks via watertight doors and therefore is not included in any of the connected volumes considered. Note that all variations have the same SOLAS 2009 Attained Index as the reference design as there has been no change to the subdivision of the vessel.

Removal of WTD204 marginally improves the A_{WTD} (0.08%) whilst re-assigning door WTD204 as category D also improves the A_{WTD} but by just over 50% of the improvement realised by removing the same door.

9.5.3 Cost Benefit Assessment

The cost benefit assessment is based on the same assumptions as in task 1 for collision. Also the ∆PLL is calculated based on the risk model for collision as the parametric model is also based on the attained index for collision.

The overview of costs for the different design variations is shown in the following table.

Table 52 Ship 5 – summary of cost benefit assessment.

Version	M21	M21_1	M21_2
Description	Reference	Remove WTD204	Change category WTD204
Attained Index A collision	0.8426	0.8426	0.8426
A_{WTD}	0.8407	0.8414	0.8411
change A	0.0000	0.0007	0.0004
∆PLL	0.0000	0.0024	0.0013
NetCAF = 4 Mio $	0.0000	9,469 $	5,411 $
NetCAF = 8 Mio $	0.0000	18,938 $	10,822 $
net Present Value NPV	0 $	-17,796 $	-300 $

9.5.4 Summary

The parametric tool has been used to assess various design versions. Removal of the forward most water tight door improves the A_{WTD} index compared to the reference version and due to the nature of the modification would be below the NetCAF limits used in this assessment. However, given that the watertight doors connect the machinery spaces below the bulkhead deck it is not considered operationally viable to remove any other doors. Changing the category of the door from C to D produces an improvement in A_{WTD} but is dependent on the acceptance that the door can still be used for escape purposes.

10 DISCUSSION OF RESULTS

This project addressed the contribution of watertight doors to the portion of risk to life relating to incidents of collision, for Cruise and RoPax ship types. The contribution has been assessed based on the following tasks;

- review of historical data on WTDs operation on existing ships,
- mathematical modelling, numerical simulations, stability assessment,
- design development and optimisation for reduction of this risk contribution.

Patterns of watertight doors usage have been analysed based on data from on-board recording systems for Cruise and RoPax passenger ship types. It was observed that typically a number of one or more WTDs are in frequent use during voyages, and majority of doors remain opened in ports. It has been noted that use of WTD is affected by its category. Namely, the averaged proportion of time the C category doors remain opened at sea is 11% and for A or B category doors it is 60%, although permitting A category door opened for 100% of the time has also been observed. The averaged duration a C category door remained opened was 1.33 minutes, with some doors opened/closed within slightly shorter, and some within much longer time span.

Assessment of the impact of an opened WTD on stability has led to an observation that the impact of any one single door, while varying from door to door, was found to be small relative to the impact of a combination of doors left opened. Furthermore, it was noted that such impact on stability was then insensitive to category of doors comprising the combination, that is, an opened door of category C or A would degrade stability on average to an equal extent.

A simplified mathematical model was developed to quantify this impact based on only a handful of relevant parameters. Namely, the model is based on the number of WTDs, their category, volume of connected spaces, total buoyant volume of the ship, time of the crew response to flooding situation, duration of doors opening and closure, and the rates of WTD failures (reliability). The construct of this model was a result of a compromise between simplicity, robustness and the accuracy. It was found that the spread in results derived by the simplified mathematical model was of the order of +/- 20% from the results derived through expensive direct calculations. Some of the parameters such as the location are only taken into account indirectly through the connected volume.

The application of this parametric model on RoPax ships needs to be further investigated as the pros and cons of the inclusion of the RoRo cargo deck in the total buoyant volume has been discussed among the partners and the impact needs to be further investigated to improve robustness of the model.

Whilst it is recommended that further study continue on possible refinements of the proposed approach, it was found during the course of the ship design and optimisation tasks that reasonable trends can be identified and viable design improvements can be put forward on the basis of calculations by the proposed approach.

For instance, the design studies have confirmed that new ships can be designed without the need for category A doors with considerable risk reduction, a fact which also has been considered by SDC2 in its decision to remove for new ships the possibility of getting an exemption for watertight doors to keep them open while at sea. Installation of multiples of doors of B or A category can contribute to risk to life significantly, with observed 56% increased risk because of many such doors designed on Ship #1. Hence this observation alone bears significant potential for tangible risk reductions.

The analysis of the existing ships also highlights that in some designs the use of doors is vital for the operation of ships. In particular for RoPax vessels it is the only way to reach other parts of the ship during normal watch keeping, as the bulkhead deck is blocked by the cargo deck.

The sensitivity of the model to the input information allows stressing the importance of operational procedures onboard. Efficient and timely crew response to flooding situation can significantly reduce the risk to life of those onboard. Conversely, lack of appropriate training or inefficient operational procedures can significantly increase risk to life above levels tolerated by regulations. The mathematical model can aid disclosure of these risks for design as well as for daily ship operation, for better awareness and training.

11 RECOMENDATIONS

Based on the analyses performed and/or contributed to by a team of design offices, ship yards, class societies, operators, and academic establishments participating in this study, the following set of recommendations is put forward for reduction of contribution to risk to life by installation and operation of watertight doors on ships.

Remove or minimize the number of category A or B doors.
Design doors only for expedient pass through.

This is the most cost-effective risk control option identified in this project. Type A and B doors need to be minimized not only on newly build ships but also for the existing fleet. It is assumed that the real-life ship operation of WTDs adheres to MSC.1/Circ.1380 guidelines.

Improve onboard monitoring to quantify impact of WTDs explicitly
Improve training for emergencies.

The mathematical model proposed facilitates robust quantitative assessment of impact of opening of door combination on the risk. Such disclosure can be used for training onboard, policing and culture development for prudent use of WTDs. It is expected that significant reduction in the frequency of usage of WTD can be achieved, and crew preparadness for effective management of undesirable events of flooding prioritised.

Crew preparedness resulting to closure of WTD immediately, with no longer delay than 2 minutes, is particularly potent risk control measure that can be implemented for existing fleet of ships.

Improve design guidelines

It is recommended that guidelines to designers and operators on minimisation of the number of watertight doors on Tank Top level, as well as arranging access to compartments below bulkhead deck through upper deck levels, be developed and promoted. To achieve this, a closer cooperation between operators and designers is needed already in the conceptual design phase to avoid any design which may require the frequent usage of WTD.

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[24] SDC 2/WP.1 "*Draft report to the Maritime Safety Committee*" London, 20 February 2015

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Appendix 1 Historical observations and analyses of the on-board records of water tight doors operation

Historical observations

According to a leading insurance firm, [4], [5], people have been trapped, maimed and killed in such doors, or non-closure of WTD has contributed to capsizing and sinking of ships. The deaths rate of approximately 1 person per year is reported in [5], with some reported indicative incidences involving WTD operations re-listed below for convenience, and indicatively only.

- 1981 Canadian vessel
- 1990 Canadian vessel
- 1998 Ro-Ro pax P&OSL Kent
- 1999 FSO Nordic Apollo
- 2001 Mobile Offshore Drilling Unit
- 2002 Passenger vessel (DNV rep.)
- 2005 Offshore installation Kristin
- 2006 Container vessel (Britannia)
- 2008 Ro-Ro cargo Ark Forwarder
- 2009 Pax vessel Oceanic Discoverer

Some examples of stability-related accidents involving opened WTD are listed as follows, [1], [5], [5], [16], [17], [18], [19], [20].

- QUEEN OF THE NORTH - grounding damage.
- EXPRESS SAMINA - grounding damage.
- STENA NAUTICA – collision damage.
- SEA DIAMOND - grounding damage.
- PRIDE OF TELEMARK - contact damage with pier foundation.
- MONARCH OF THE SEAS - grounding damage.
- MV ESTONIA – lost bow visor.

Although the non-closure of WTD is reported to have contributed to the risk and to the chain of causation in each of these accidents, there appear to be no quantitative statements as to the exact extent of these contributions.

Operational data

Information about watertight door operation for four ships (two Cruise and two RoPax) was derived from onboard records. Information extracted for analyses comprised watertight doors status and loading conditions. Weather conditions were not available in any of the systems.

The analysed patterns of operation addressed frequencies of use of WTD and frequencies of exposure of spaces connected by these doors. The latter concerns specifically ratio Vcn/V_{DH}, a ratio of V_{cn} (volume of spaces connected by opened WTD) to V_{DH} (volume of DAMHULL, geometry used for stability assessment).

Data for Cruise 1 had frequency of recording of 2 hours, hence in excess of the above resolution. Data for Cruise 2 did not contain indicators of sail or port conditions.

The resolution of data (sampling rates) for both loading and water tight doors status for Cruise1 was approximately every two hours. The resolution of status of water tight doors for the remaining ships was at approximately 1 second, wheras the resolution of data for loading for these ships was low at approximately every 12 to 24 hours.

The analyses are presented in the remaining parts of this Appendix, including Table 53 to Table 59, and Figure 20 to Figure 46.

The statistics considered of most relevance for the study were the averaged proportion of time doors remain opened, listed in Table 2, and the averaged duration of single operation of opening and closing a door, listed in Table 3. The averaged proportion of time the C category doors remain opened at sea is 11%, for B category doors it is 60%, and for A category door it is assumed 100%. The averaged duration a C category door remains opened is 1.33 minutes.

Cruise 1

Table 53 lists the WTD doors on Cruise 1 together with some descriptive characteristics, such as name and location, as well as statistical analyses inferred from the onboard data shown in Figure 20 and Figure 23 relating to the frequency of doors operation. Namely, the last two columns of Table 53 show the percentage of instances when a particular door was recorded as remaining opened, at all times or only at times when the vessel was at sea, respectively. Since the records were taken every two hours, it is impossible to state how long doors remained opened. Rather, these records inform consistently about likelihood that a particular door may be opened at an unknown instant of a flooding incident. These statistics were derived for every door, based on data recorded for two weeks, and hence may be considered robust.

Subsequent Table 54 provides with similar statistics of operation, but for a set of one …, two …, three …, etc …, … of doors all remaining opened at the same instance in time. It is perhaps first observation to infer from this table, that up to four doors remain opened at all times on this ship, at sea or in port. Closer examination of Figure 20 and Figure 23 reveals that this is the case with A category doors, which being exempt, are likely to remain opened at all times.

Figure 22 and Figure 25 show distribution of the frequency of doors operation listed in Table 53, for longitudinal and vertical location of doors on each of the figures, and for operation at ports and sea, or sea only, respectively. These figures support the notion that usage of watertight doors is more frequent in machinery locations, and is less and less frequent away from these locations. Occasionally doors are used more frequently when exempt.

Figure 21 and Figure 24 show the distribution of the ratio of Vcn/VDH resulting due to the operation for doors at ports and sea, or sea only, respectively. Perhaps the noticeable aspect of the ratio is that it appears constant with Vcn/VDH close to 0.17 whether the ship is in port or at sea. The reason for this is that this ratio is dominated by the doors of category A, which have similar pattern of usage at all times. The ratio reaches 0.37 when the ship operates in port, with many doors remaining opened.

Cruise 2

Table 55 lists the WTD doors on Cruise 2 together with some descriptive characteristics, such as name and location.

The data available for Cruise 2 are shown in Figure 27. A sample screenshots from the onboard system for review of doors status is shown in Figure 26.

The data proved of use for assessment of duration of doors operation, characterised by distribution of probability for it, as shown in Figure 28. The expected time for the door of category C to remain opened was found to be 1.84 minutes for Cruise 2.

Ropax 1

Table 56 lists the WTD doors on RoPax 1 together with some descriptive characteristics, such as name and location, as well as statistical analyses inferred from the onboard data shown in Figure 30 and Figure 34 relating to the frequency of doors operation. The last two columns of Table 56 show the percentage of instances when a particular door was recorded as remaining opened, at all times or only at times when the vessel was at sea, respectively. These records inform consistently about likelihood that a particular door may be opened at an unknown instant of a flooding incident. These statistics were derived for every door, based on data recorded for one week at very high frequency of up once per second, and hence may be considered robust.

Figure 29 provides with convenient breakdown of operation of opening or closing per day, for each of the doors. It may be noted, that the doors in machinery spaces is used nearly twice as much as any other doors on the ship.

Subsequent Table 57 provides with similar statistics of operation, but for a set of one …, two …, three …, etc …, … of doors all remaining opened at the same instance in time. This data confirms the observation from Cruise 1, namely that many doors are left opened whilst at port. On the other hand, whilst the ship is at sea, the WTD’s are mostly closed.

Figure 33 and Figure 37 show distribution of the frequency of doors operation listed in Table 56, for longitudinal and vertical location of doors on each of the figures, and for operation at ports and sea, or sea only, respectively. As with earlier observations, these figures support the notion that usage of watertight doors is more frequent in machinery locations, and is less and less frequent away from these locations.

Figure 33 and Figure 36 show the distribution of the ratio of Vcn/VDH resulting due to the operation for doors at ports and sea, or sea only, respectively. The difference between these ratios calculated inclusive of times at port and only at sea is quite profound. This results mainly because only category of C doors are used and these doors remain closed most of the time when at sea. During times at port, it appears, the doors are used far more frequently for horizontal operations.

Ropax 2

In simialr manner as above, Table 58 lists the WTD doors on RoPax 2 together with some descriptive characteristics, such as name and location, as well as statistical analyses inferred from the onboard data shown in Figure 39 and Figure 43 relating to the frequency of doors operation. The last two columns of Table 58 show the percentage of instances when a particular door was recorded as remaining opened, at all times or only at times when the vessel was at sea, respectively. These records inform consistently about likelihood that a particular door may be opened at an unknown instant of a flooding incident. These statistics were derived for every door, based on data recorded for one week at very high frequency of up once per second, and hence may be considered robust.

Figure 38 provides with convenient breakdown of operation of opening or closing per day, for each of the doors. It may be noted, that the doors between engine room and workshop spaces is used nearly twice as much as any other doors on the ship. On the other hand, an exempt category A door No2 is never operated, as it remains opened at all times.

Subsequent Table 59 provides with similar statistics of operation, but for a set of one …, two …, three …, etc …, … of doors all remaining opened at the same instance in time. This data confirms the observation from Cruise 1 or RoPax 1, namely that many doors are left opened more often whilst at port.

Figure 42 and Figure 46 show distribution of the frequency of doors operation listed in Table 58, for longitudinal and vertical location of doors on each of the figures, and for operation at ports and sea, or sea only, respectively. As with earlier observations, these figures support the notion that usage of watertight doors is more frequent in machinery locations, and is less and less frequent away from these locations, although in case of this ship an exempt door (category A) remains opened at all times for spaces.

Figure 39 and Figure 43 show the distribution of the ratio of Vcn/VDH resulting due to the operation for doors at ports and sea, or sea only, respectively. The difference between these ratios calculated inclusive of times at port and only at sea is considerable. This results mainly because only category of C doors are used and these doors remain closed most of the time when at sea.

Cruise 1

Table 53 List of connected spaces by WTD of Cruise 1. Statistics of operation of single doors.

No	Space1	Space2	Category	x/Lbp	y/B	z/draught	% of instances remaining opened (at port and at sea)	% of instances remaining opened (at sea only)
1	Machinery space	Machinery space	C	0.400	0.324	0.215	63.29	57.14
2	MEME room	Machinery space	B	0.337	0.053	0.215	69.62	70.59
3	MEME room	MEME room	C	0.269	0.060	0.215	82.91	83.19
4	Machinery space	MEME room	B	0.212	0.046	0.215	70.25	66.39
5	Serv. corridor	Laundry	B	0.713	-0.038	0.473	60.13	57.14
6	Crew stairs	Service lift	C	0.713	0.246	0.473	3.16	2.52
7	Serv. corridor	Serv. corridor	C	0.650	0.239	0.473	21.52	14.29
8	Serv. corridor	Serv. corridor	B	0.587	0.239	0.473	58.86	54.62
9	Machinery space	Serv. corridor	C	0.463	0.333	0.473	31.65	25.21
10	Thruster room	Thruster room	C	0.915	0.023	0.763	5.06	4.2
11	Crew cymnasium	Thruster room	C	0.879	0.032	0.763	10.76	11.76
12	Lift/crew lobby	Crew cymnasium	C	0.839	0.187	0.763	11.39	11.76
13	Serv. corridor	Serv. corridor	B	0.776	0.142	0.763	58.23	52.94
14	Crew cabin	Crew cabin	C	0.650	0.016	0.763	3.8	3.36
15	Crew cabin	Crew cabin	C	0.587	0.014	0.763	0.63	0
16	Crew cabin	Crew cabin	C	0.463	-0.009	0.763	1.27	0
17	Crew cabin	Crew cabin	C	0.399	0.000	0.763	0.63	0
18	Machinery space	Machinery space	C	0.149	0.219	0.763	13.29	12.61
19	Crew cabin	Crew cabin	C	0.776	0.011	1.065	0.63	0
20	Crew cabin	Crew cabin	C	0.713	-0.143	1.065	0.63	0
21	Crew cabin	Crew cabin	C	0.587	0.001	1.065	0.63	0
22	Crew cabin	Crew cabin	C	0.400	-0.004	1.065	0.63	0
23	Serv. corridor	Serv. corridor	B	0.159	0.008	1.065	54.43	48.74
24	Serv. corridor	Serv. corridor	B	0.087	0.000	1.065	55.7	50.42
25	Serv. corridor	Serv. corridor	O	0.266	-0.469	1.360	1.27	0
26	Crew mess	Crew stairs	A	0.844	0.134	1.360	20.25	25.21
27	Crew mess	Crew stairs	A	0.844	0.166	1.360	63.29	62.18
28	Crew stairs	Crew stairs	C	0.844	0.259	1.360	18.99	21.01
29	Crew mess	Crew mess	A	0.839	-0.166	1.360	79.11	79.83
30	Crew mess	Crew mess	A	0.839	-0.133	1.360	32.91	29.41
31	Crew mess	Crew mess	B	0.776	-0.293	1.360	48.1	44.54
32	Crew mess	Crew mess	B	0.776	-0.325	1.360	51.27	46.22
33	Galley	Crew mess	A	0.776	0.153	1.360	98.73	98.32
34	Serv. corridor	Galley	B	0.776	0.321	1.360	99.37	99.16
35	Crew cabin	Hall	C	0.713	-0.371	1.360	0	0
36	Hall	Crew cabin	C	0.713	0.371	1.360	3.16	4.2
37	Crew cabin	Crew cabin	C	0.587	-0.371	1.360	1.27	0.84
38	Crew cabin	Crew cabin	C	0.587	0.371	1.360	0	0
39	Luggages	Crew cabin	C	0.494	-0.365	1.360	0	0
40	Luggages	Crew cabin	C	0.486	0.365	1.360	0.63	0.84
41	Crew cabin	Luggages	C	0.463	-0.365	1.360	0	0
42	Crew cabin	Luggages	C	0.463	0.365	1.360	1.9	0
43	Crew cabin	Crew cabin	C	0.397	-0.346	1.360	28.48	21.85
44	Crew cabin	Crew cabin	C	0.400	0.365	1.360	49.37	47.9
45	Pass. corridor	Hall	A	0.337	-0.135	1.360	0	0
46	Pass. corridor	Hall	A	0.337	0.135	1.360	98.73	98.32
47	Crew cabin	Crew cabin	A	0.337	0.369	1.360	100	100
48	Crew corridor	Crew cabin	C	0.266	-0.371	1.360	1.27	0
49	Garbage room	Luggages	C	0.212	-0.291	1.360	7.59	5.88
50	Office	Luggages	C	0.212	0.374	1.360	0.63	0
51	Pass. corridor	Hall	C	0.713	0.128	1.360	0	0

Table 54 Cruise1 - statistics of operation of combination of doors.

Number of doors opened	% of instances (at port and at sea)	% of instances (at sea)
0	0	0
1	0	0
2	0	0
3	0	0
4	0	0
5	2.45	2.52
6	5.14	5.04
7	5.7	5.88
8	9.49	10.92
9	3.8	4.2
10	6.96	9.24
11	5.7	5.88
12	3.16	3.36
13	1.27	1.68
14	1.9	2.52
15	1.27	1.68
16	3.16	4.2
17	5.06	5.04
18	10.76	9.24
19	10.76	8.4
20	5.06	4.2
21	5.06	4.2
22	4.43	4.2
23	2.53	3.36
24	3.16	2.52
25	2.53	1.68
35	0.02	-
36	0.61	-

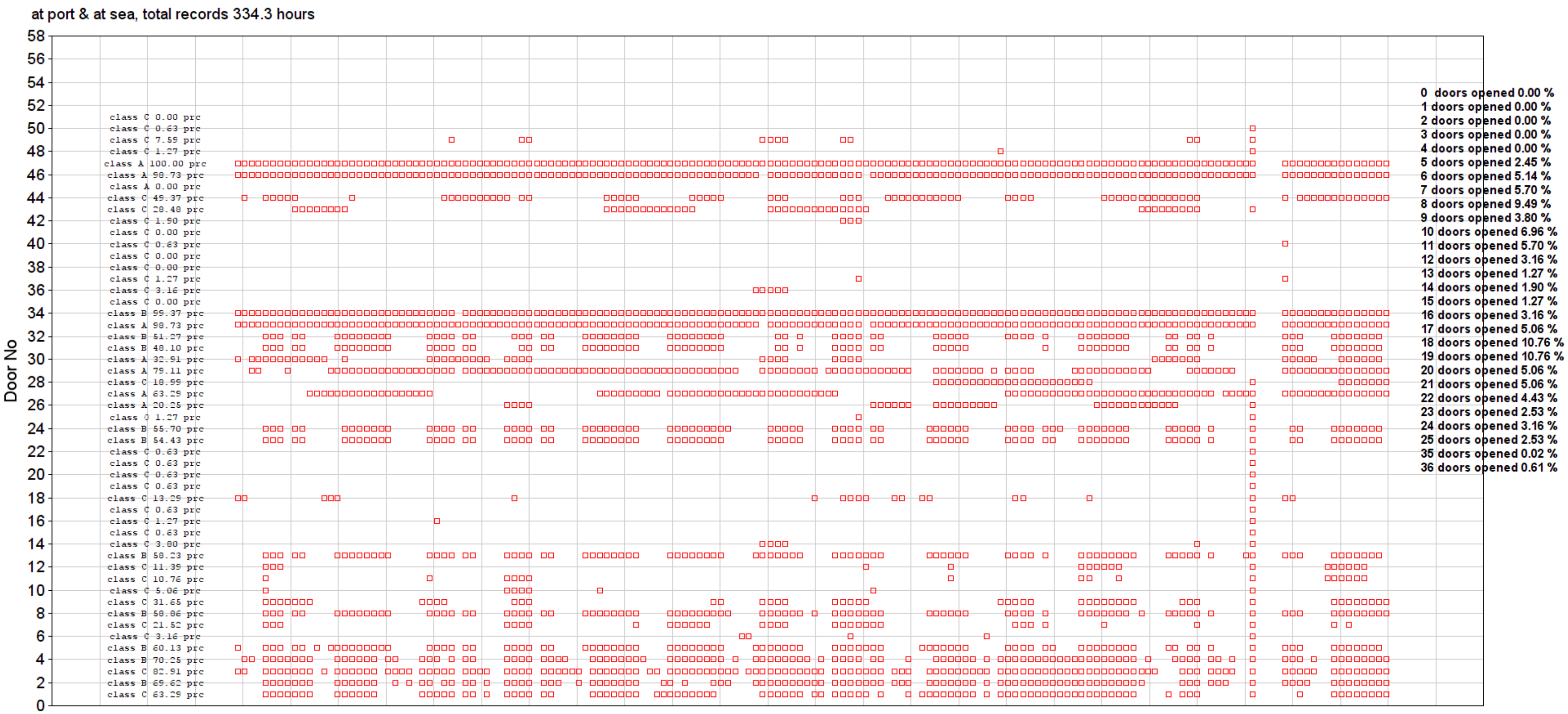

Figure 20 Cruise 1, instances of doors openings at sea and in port in time, over two week period.

Frequency of records shown in the above figure was approximately once every two hours. Every instance marked by the red square indicates opened door at one instance in time (the amount of time a door remains opened is not shown).

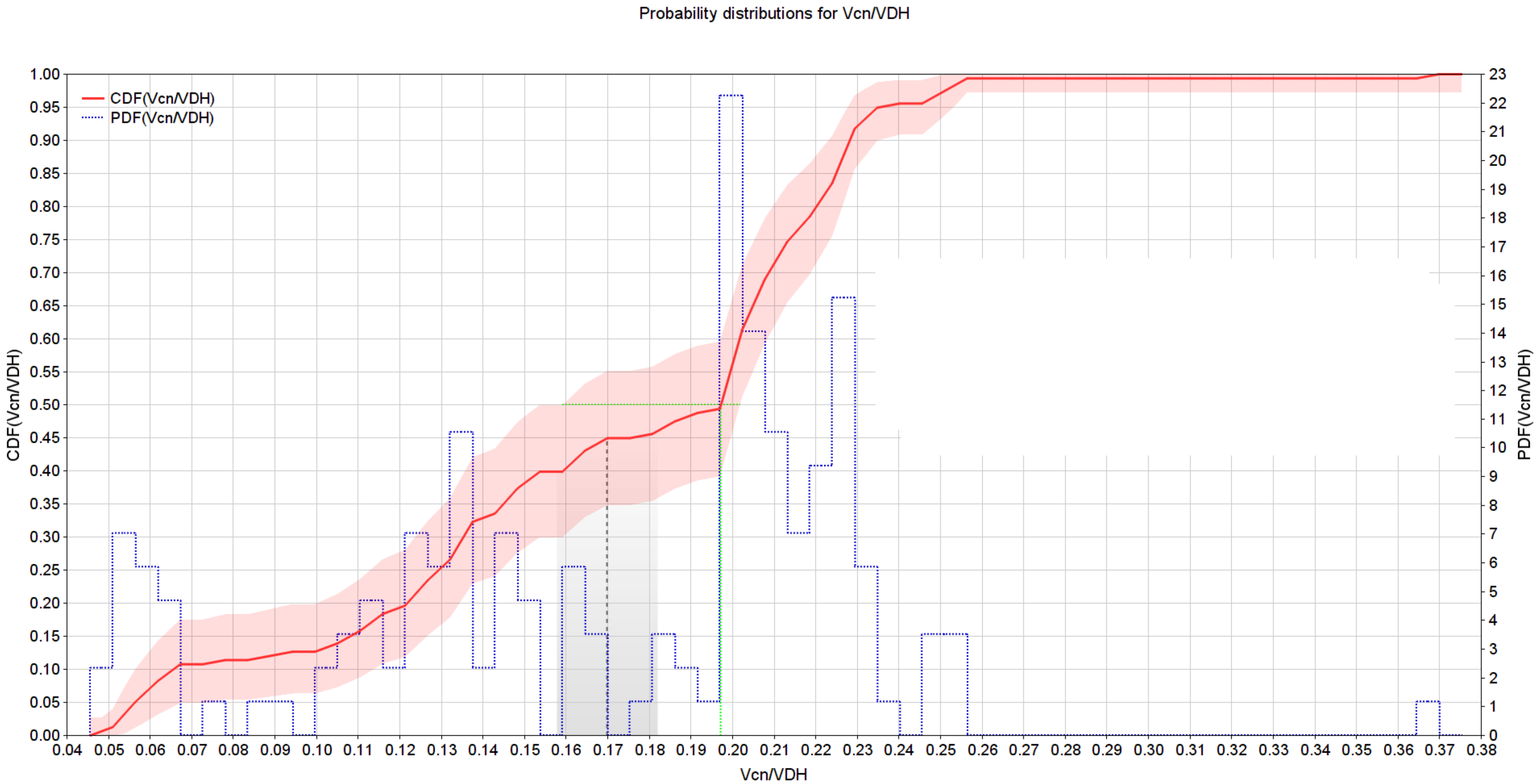

Figure 21 Cruise 1, distribution of probability for the occurrence of ratio Vcn/VDH at sea and in port.

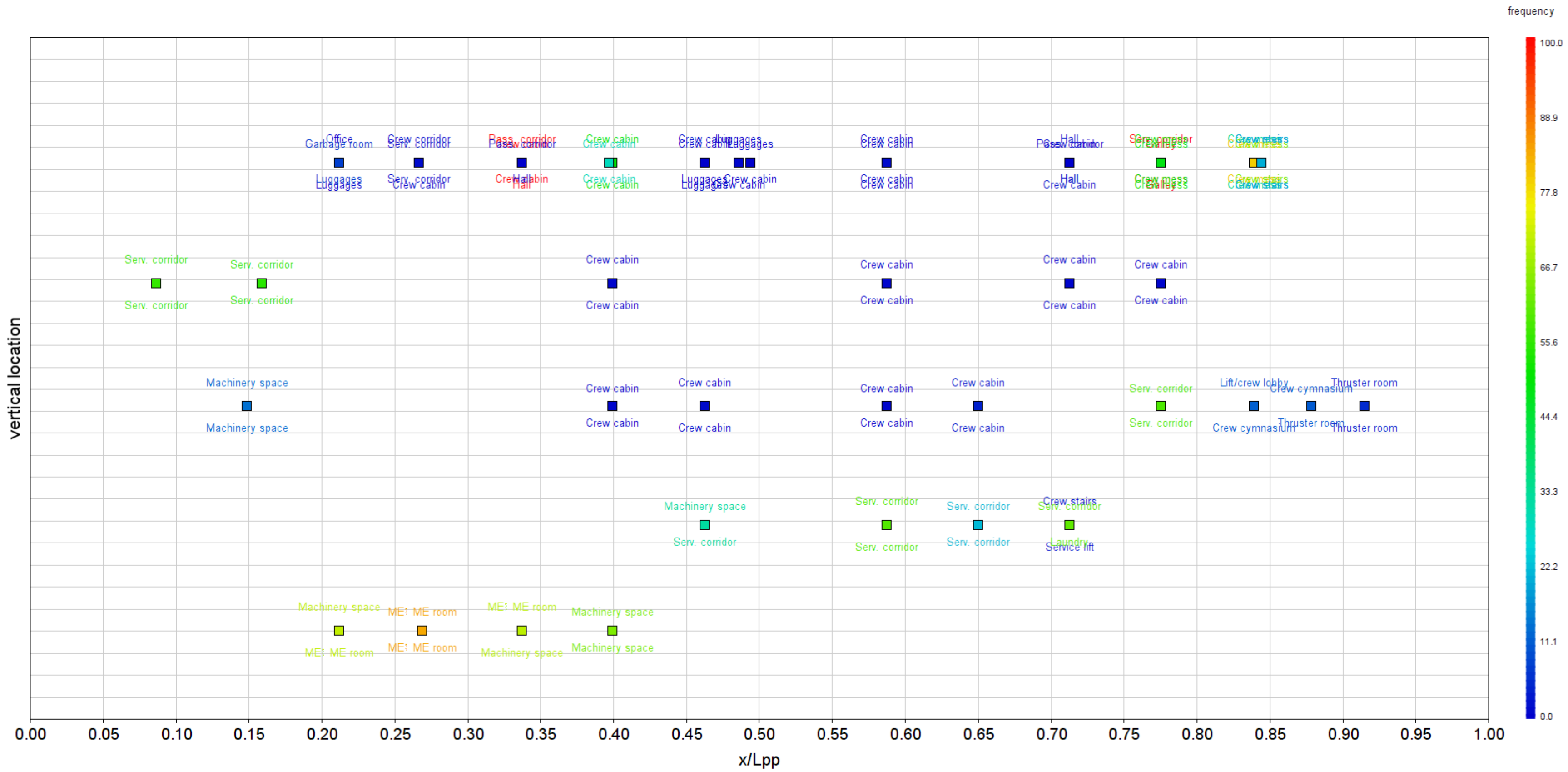

Figure 22 Cruise 1, distribution of frequency (in color) for instances of doors opening at sea and in port.

The distribution is shown for longitudinal and vertical doors locations. Frequency implies occurrence of opening per every instance recorded over two weeks and at two hours intervalls.

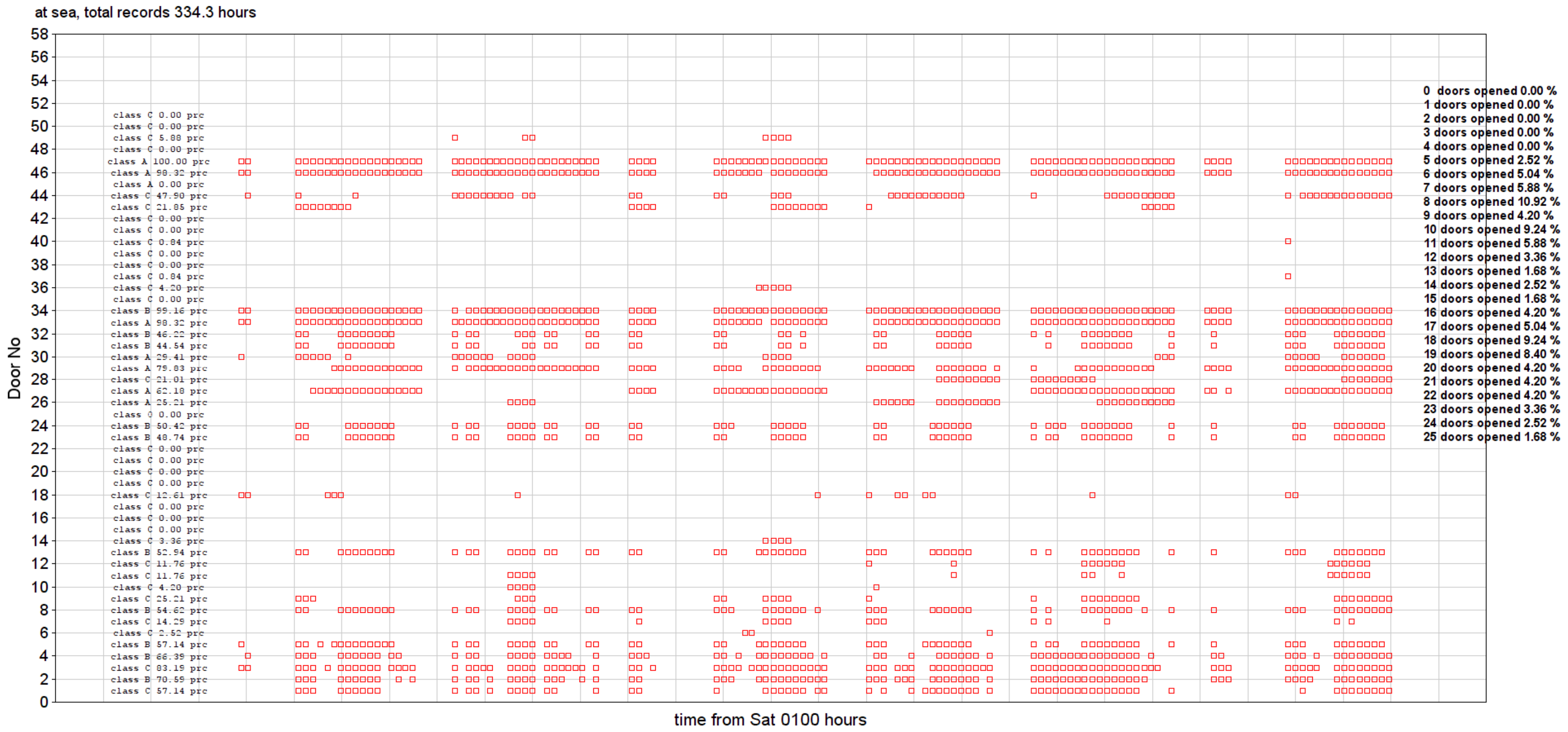

Figure 23 Cruise 1, instances of doors openings at sea only in time, over two week period.

Frequency of records shown in the above figure was approximately once every two hours. Every instance marked by the red square indicates opened door at one instance in time (the amount of time a door remains opened is not shown).

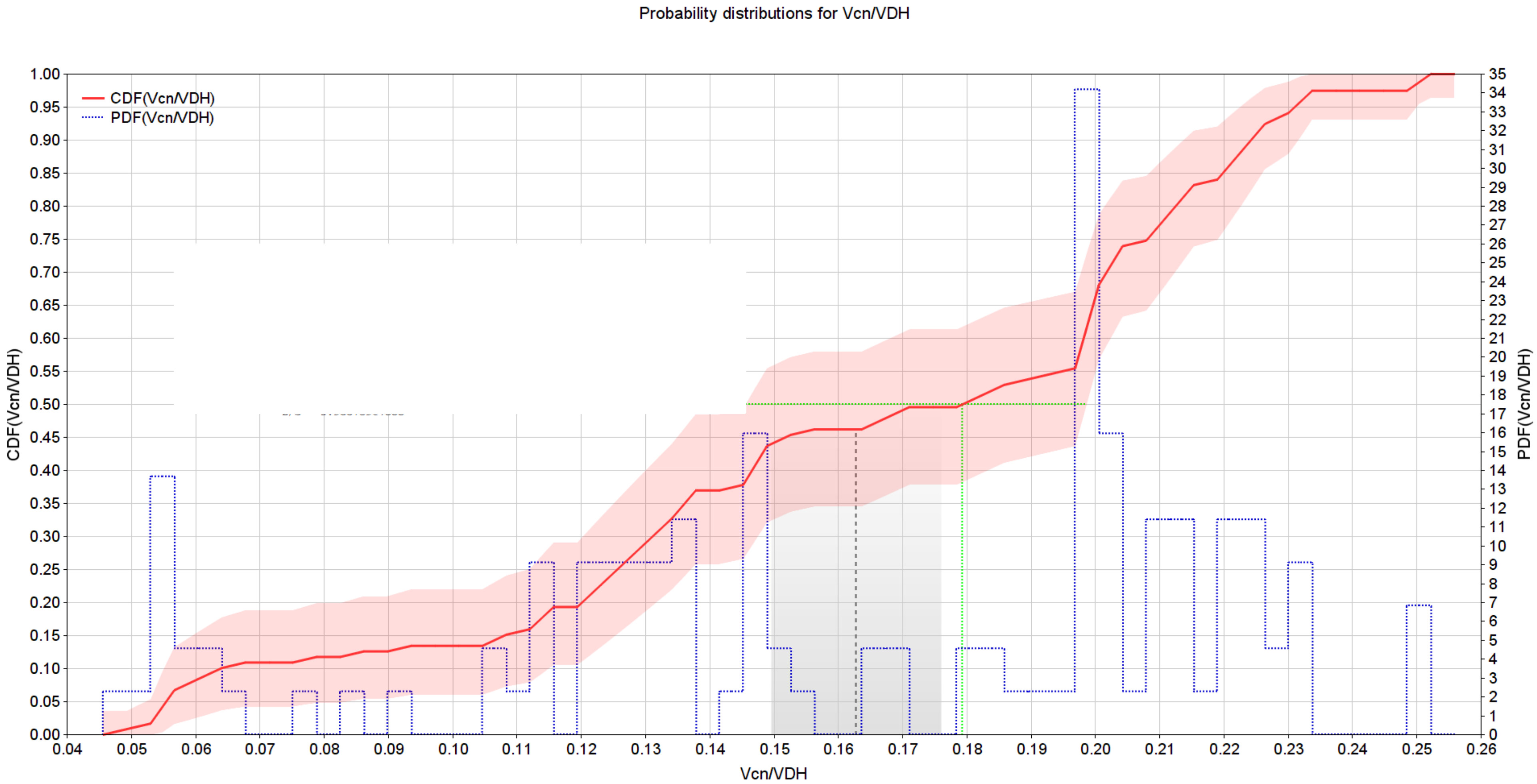

Figure 24 Cruise 1, distribution of probability for the occurrence of ratio Vcn/VDH at sea only.

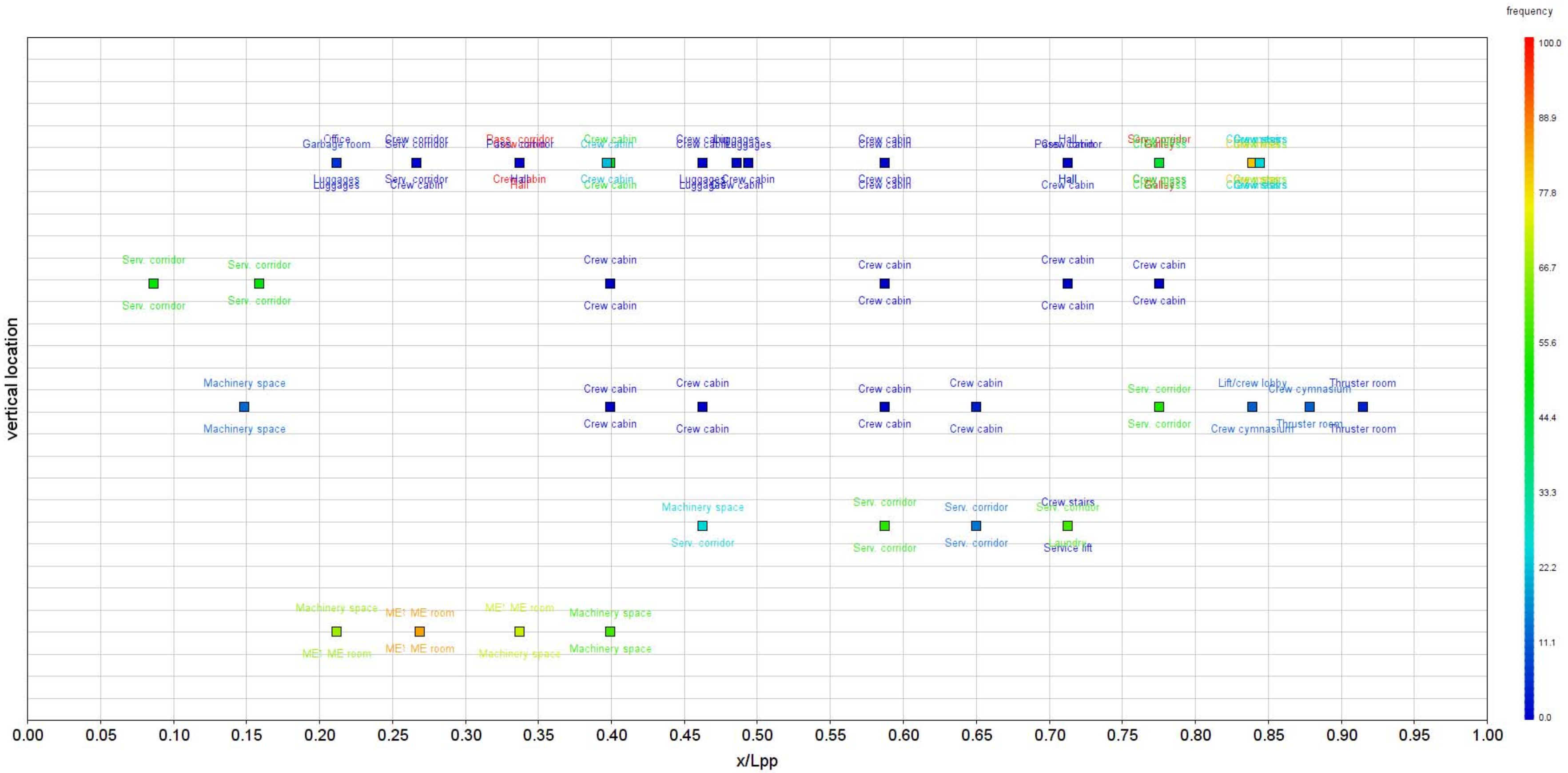

Figure 25 Cruise 1, distribution of frequency (in color) for instances of doors opening at sea only.

The distribution is shown for longitudinal and vertical doors locations. Frequency implies occurrence of opening per every instance recorded over two weeks and at two hours intervalls.

Cruise 2

Table 55 List of connected spaces by WTD of Cruise 2.

No	Space1	Space2	Category
1	Machinery_space	Machinery_space	C
2	Machinery_space	Machinery_space	B
3	Machinery_space	Machinery_space	C
4	Machinery_space	ME_room	B
5	ME_room	ME_room	C
6	ME_room	Machinery_space	B
7	Separator_room	Machinery_space	C
8	Crew_cabin	Ironing	B
9	Serv._corridor	Serv._corridor	B
10	Crew_stairs	Serv._corridor	B
11	Serv._corridor	Crew_cabin	C
12	Thruster_room	Thruster_room	C
13	Thruster_room	Crew_cabin	C
14	Crew_cabin	Crew_cabin	C
15	Crew_cabin	Crew_cabin	C
16	Crew_cabin	Crew_cabin	C
17	Crew_cabin	Crew_cabin	C
18	Crew_cabin	Crew_cabin	C
19	Crew_cabin	Crew_cabin	C
20	Crew_cabin	Crew_cabin	C
21	Crew_cabin	Crew_cabin	C
22	Crew_cabin	Crew_cabin	C
23	Crew_cabin	Crew_cabin	C
24	Crew_cabin	Crew_cabin	C
25	Crew_cabin	Crew_cabin	C
26	Crew_cabin	Crew_cabin	C
27	Crew_cabin	Crew_cabin	C
28	Crew_cabin	Crew_cabin	C
29	Crew_cabin	Crew_cabin	C
30	Serv._corridor	Machinery_space	B
31	Serv._corridor	Serv._corridor	B
32	Serv._corridor	Serv._corridor	B
33	Provision	Serv._corridor	B
34	Machinery_space	Serv._corridor	B
35	Crew_cabin	Crew_cabin	C
36	Crew_cabin	Crew_cabin	C
37	Crew_cabin	Crew_cabin	C
38	Crew_cabin	Crew_cabin	C
39	Crew_cabin	Crew_cabin	C
40	Crew_cabin	Crew_cabin	C
41	Crew_cabin	Crew_cabin	C
42	Crew_cabin	Crew_cabin	C
43	Crew_cabin	Crew_cabin	C
44	Crew_cabin	Crew_cabin	C
45	Crew_cabin	Crew_cabin	C
46	Crew_cabin	Crew_cabin	C
47	Crew_cabin	Crew_cabin	C
48	Crew_cabin	Pax_stairs	C
49	Crew_cabin	Entrance_hall	C
50	Entrance_hall	Crew_cabin	C
51	Pax_stairs	Serv._corridor	C
52	Office	Bunker_station	C
53	Crew_cabin	Bunker_station	C
54	Machinery_space	Incinerator_room	C
55	Office	Conference	C
56	Luggages	Serv._corridor	C
57	Luggages	Serv._corridor	C
58	Preparation	Provision	C
59	Provision	Preparation	C
60	Preparation	Preparation	C

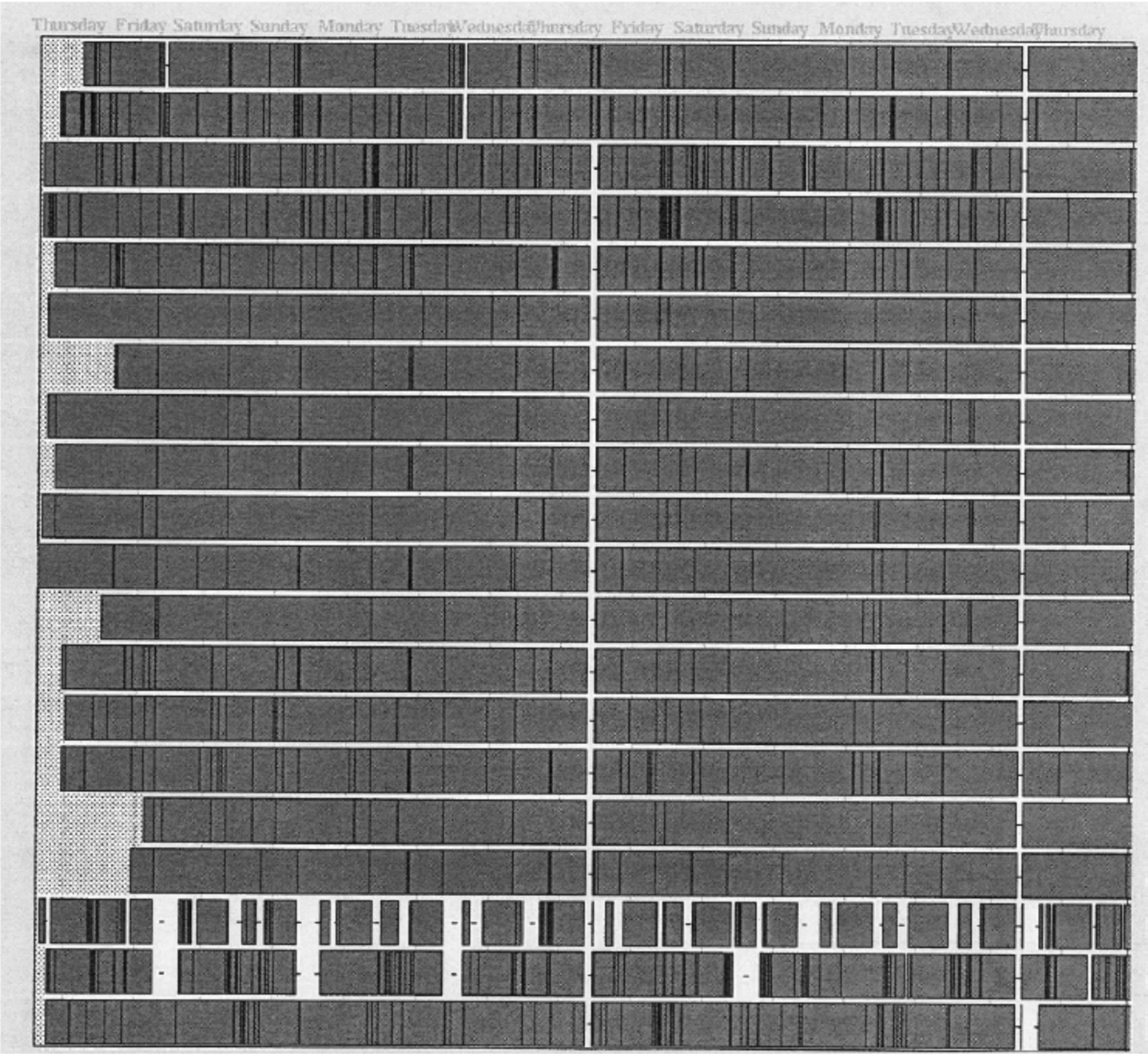

Figure 26 Cruise2, a sample screenshot of the record of doors closures at sea and in port.

Dark grey in the above figure indicates doors closed. Records in month of July. Records of doors, (from top to bottom) number 12 to 14, 16 to 29, 32 and 33, and 11.

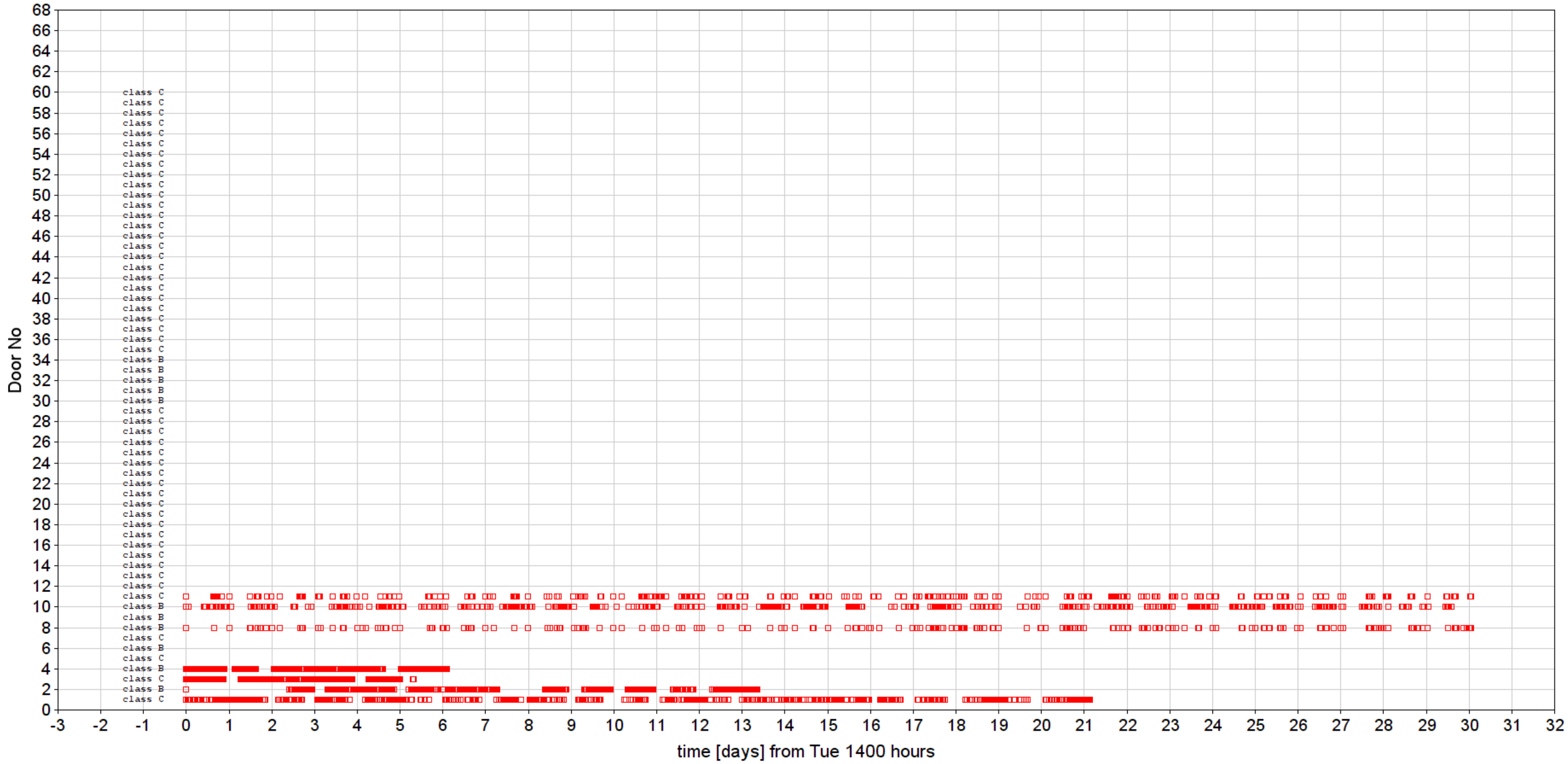

Figure 27 Cruise2, instances of doors openings at sea and in port in time (accessible digital records).

Every red square in the figure above indicates opened door at one instance in time (the amount of time a door remains opened is not shown).

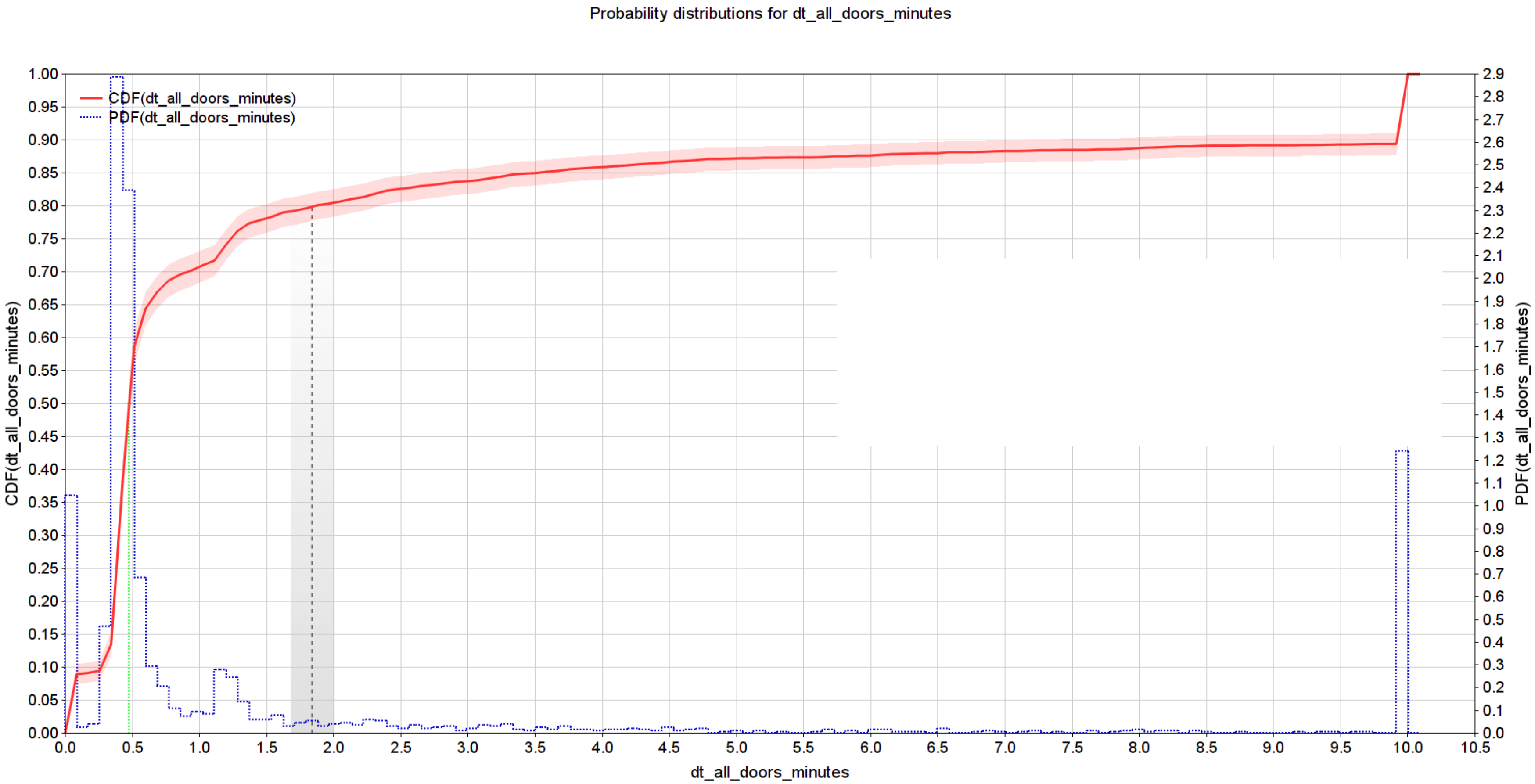

Figure 28 Cruise2, distribution of probability for the duration of opening of WTDs (C category only) at sea and in port.

RoPax 1

Table 56 List of connected spaces by WTD of RoPax 1. Statistics of operation of single doors.

No	Space 1	Space 2	Class	x/Lbp	y/B	z/draught	% of instances remaining opened (at port and at sea)	% of instances remaining opened (at sea only)
1	Void_Space	Void_Space	C	0.082	-0.039	0.881	46.5	1.3
2	Void_Space	Machinery_space	C	0.213	-0.189	0.881	50.5	5.2
3	Machinery_space	Machinery_space	C	0.217	-0.271	0.881	58.8	9.9
4	Machinery_space	Engine_store	C	0.279	-0.035	0.881	76.5	24.1
5	Engine_store	ME_room	C	0.328	-0.026	0.881	73.8	12.6
6	ME_room	AE_room	C	0.401	-0.026	0.881	70.2	8.8
7	AE_room	Separator_room	C	0.459	-0.026	0.881	63.3	5.9

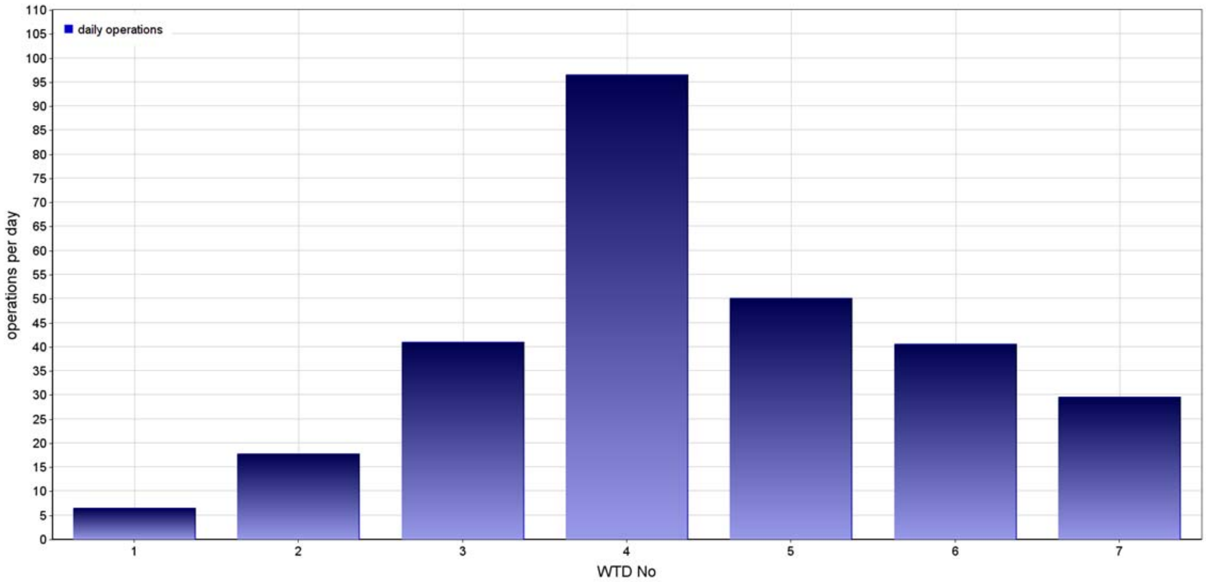

Figure 29 RoPax 1, opening operation or closing operation per day, statistics at sea and in port.

Table 57 RoPax 1 - statistics of operation of combination of doors.

Number of doors opened	% of instances (at port and at sea)	% of instances (at sea)
0	15.62	54.87
1	8.52	28.08
2	7.23	12.73
3	4.58	3.41
4	11.47	0.72
5	4.49	0.15
6	2.13	0.04
7	45.95	0

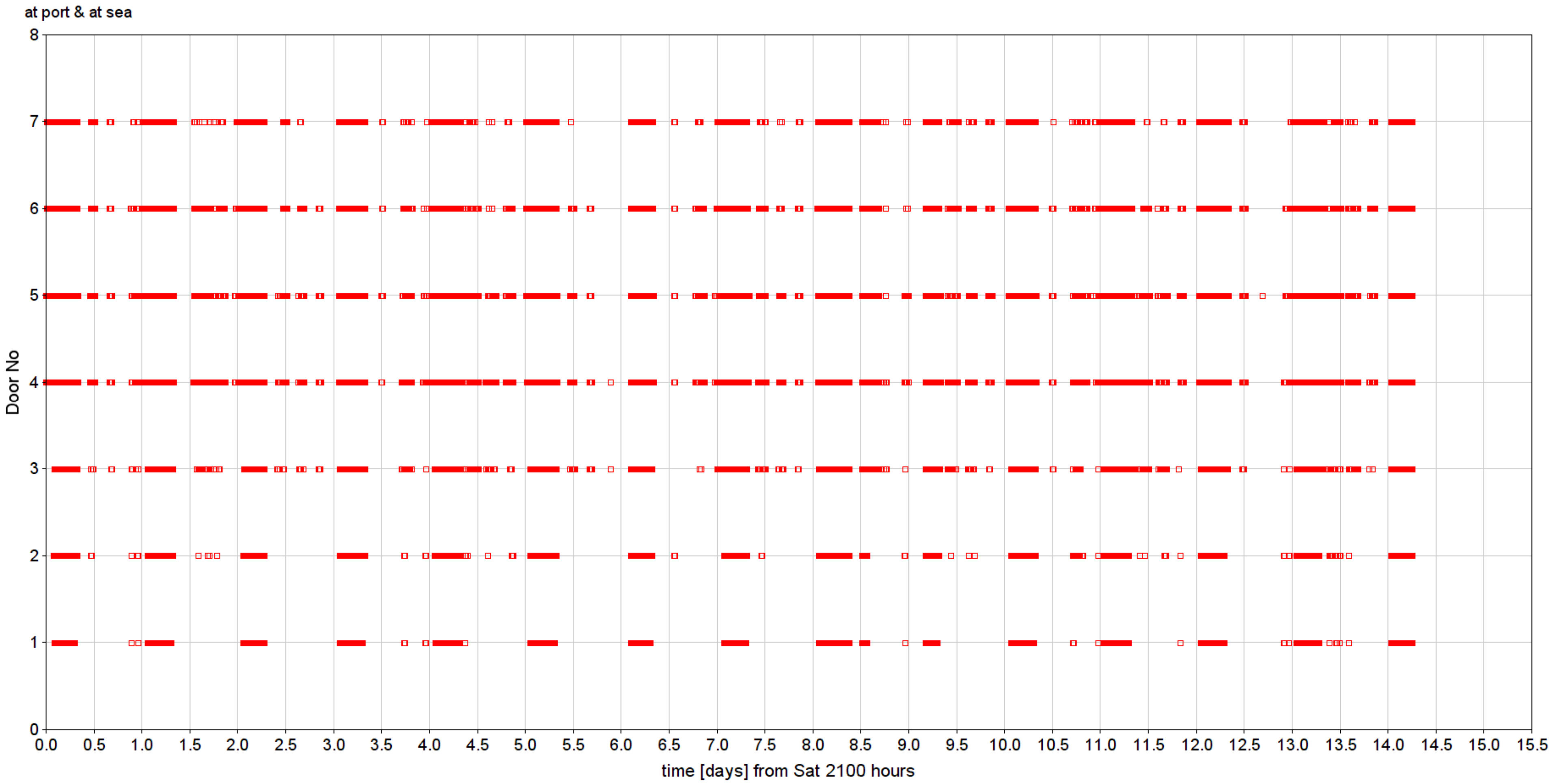

Figure 30 RoPax 1, instances of doors openings at sea and in port.

Every record indicates opened door at one instance in time (the amount of time a door remains opened is not shown).

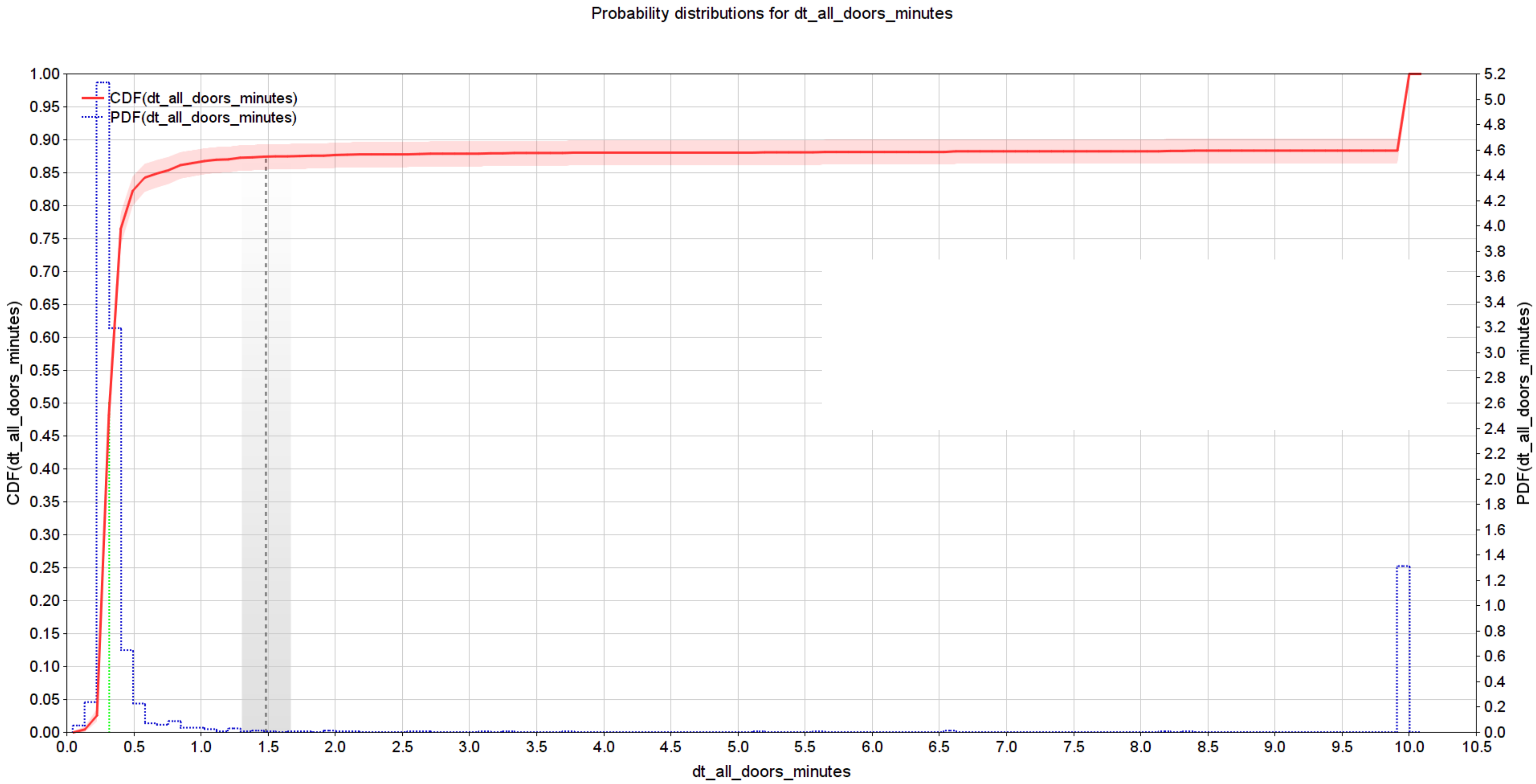

Figure 31 RoPax 1, distribution of probability for the duration of opening of WTDs (C category only) at sea and in port.

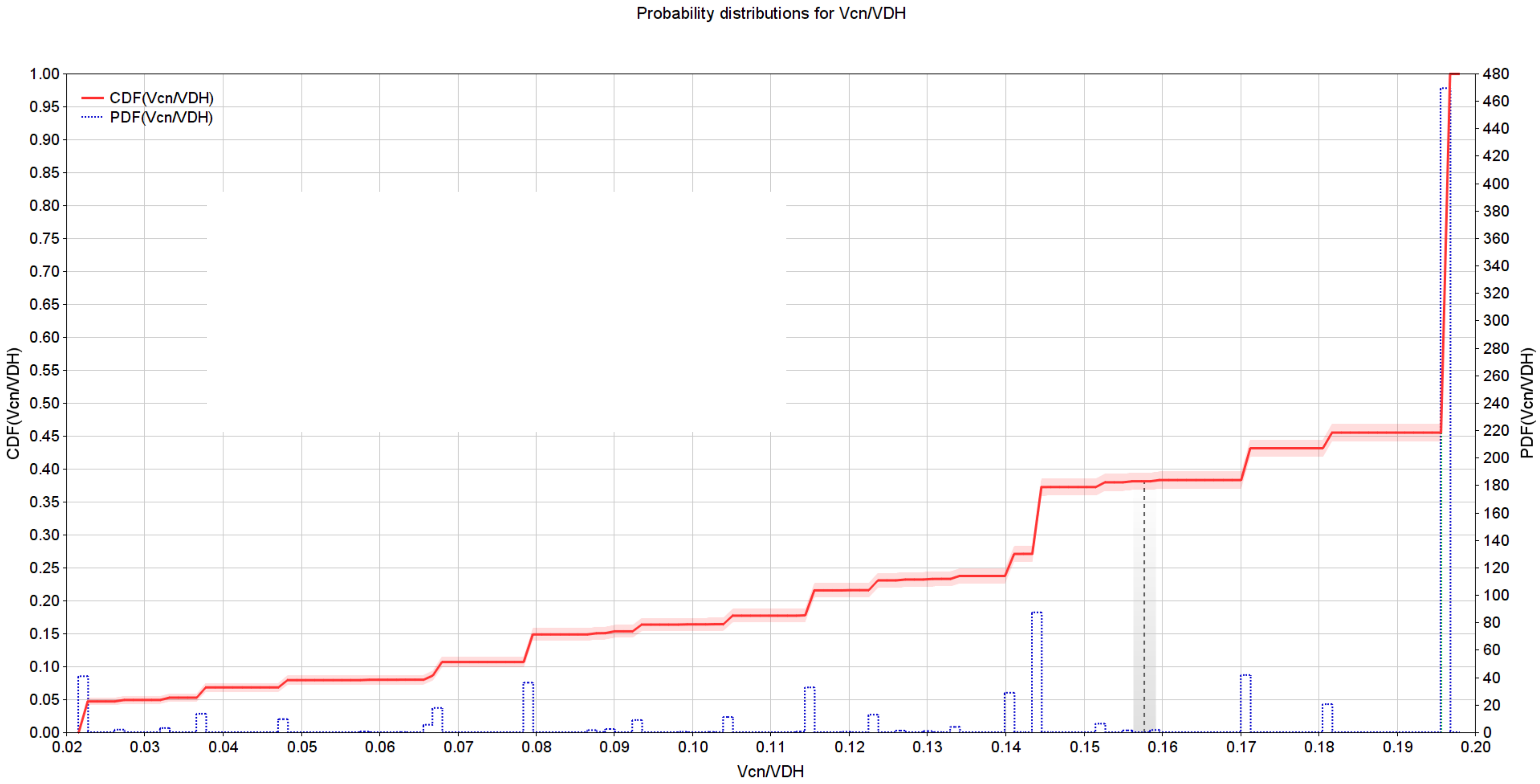

Figure 32 RoPax 1, distribution of probability for the occurrence of ratio Vcn/VDH at sea and in port.

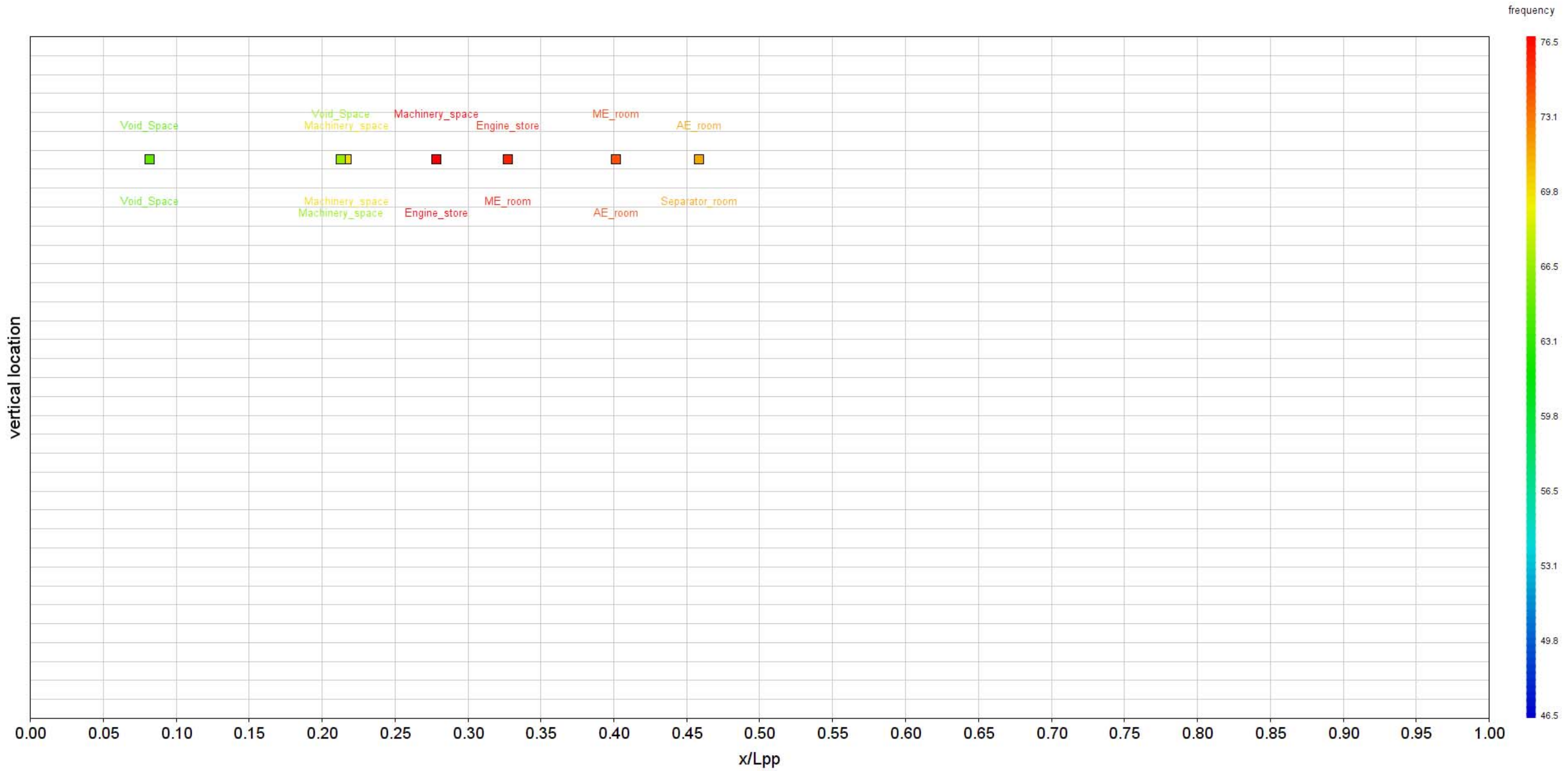

Figure 33 RoPax 1, distribution of frequency (in color) for instances of doors opening at sea and in port.

The distribution is shown above for longitudinal and vertical doors locations. Frequency implies occurrence at any time instant.

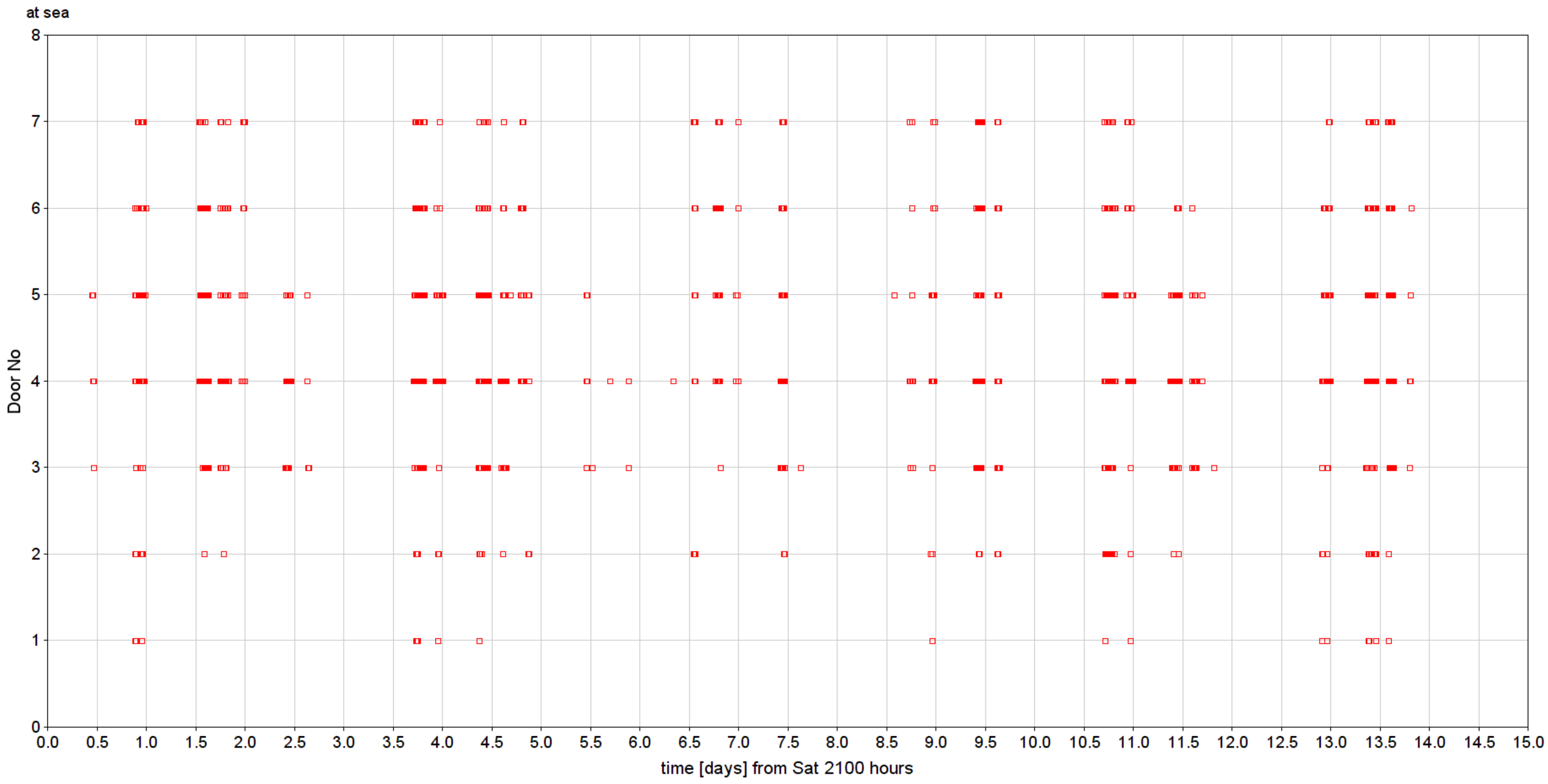

Figure 34 RoPax 1, instances of doors openings at sea only.

Every record indicates opened door at one instance in time (the amount of time a door remains opened is not shown).

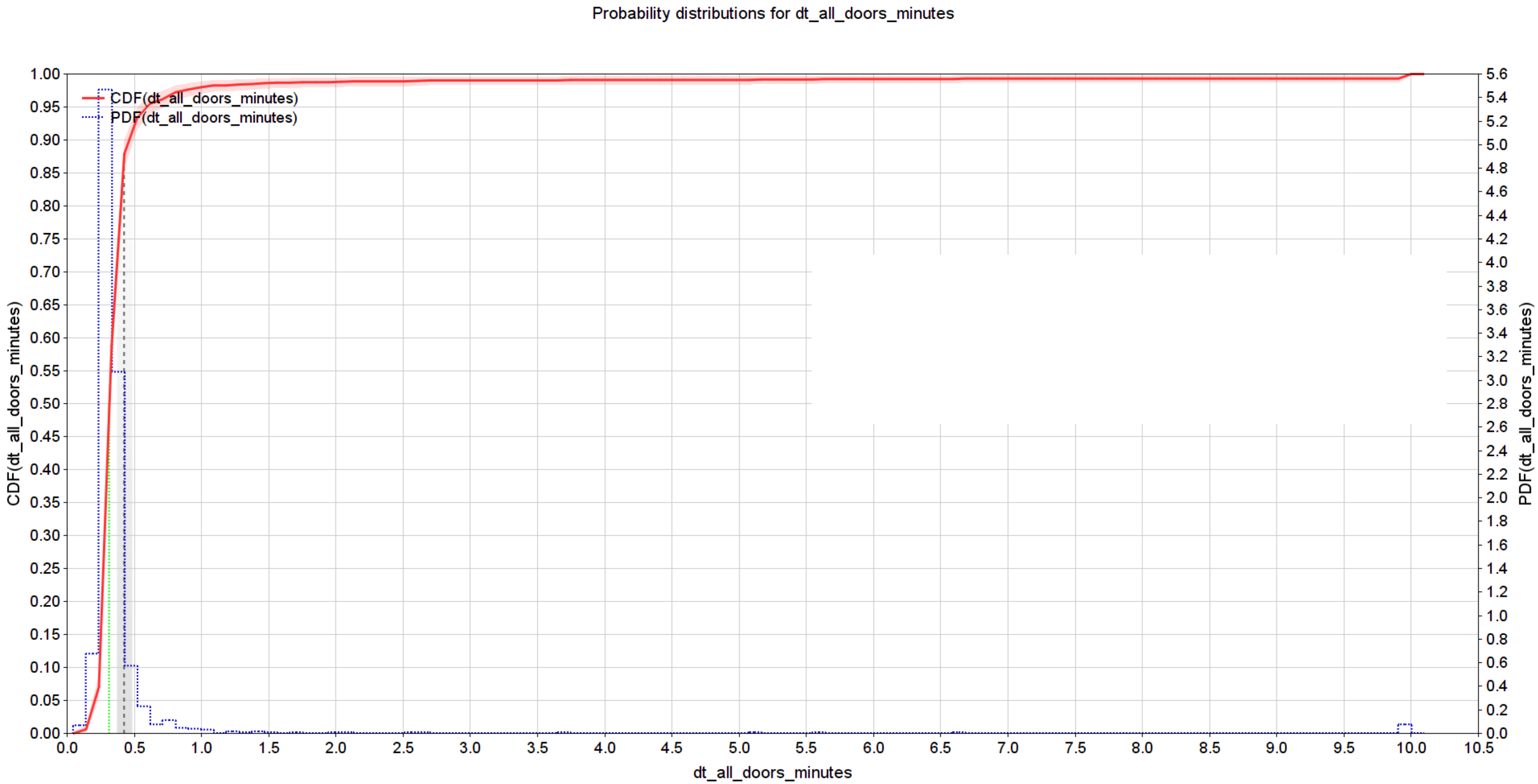

Figure 35 RoPax 1, distribution of probability for the duration of opening of WTDs (C category only) at sea only.

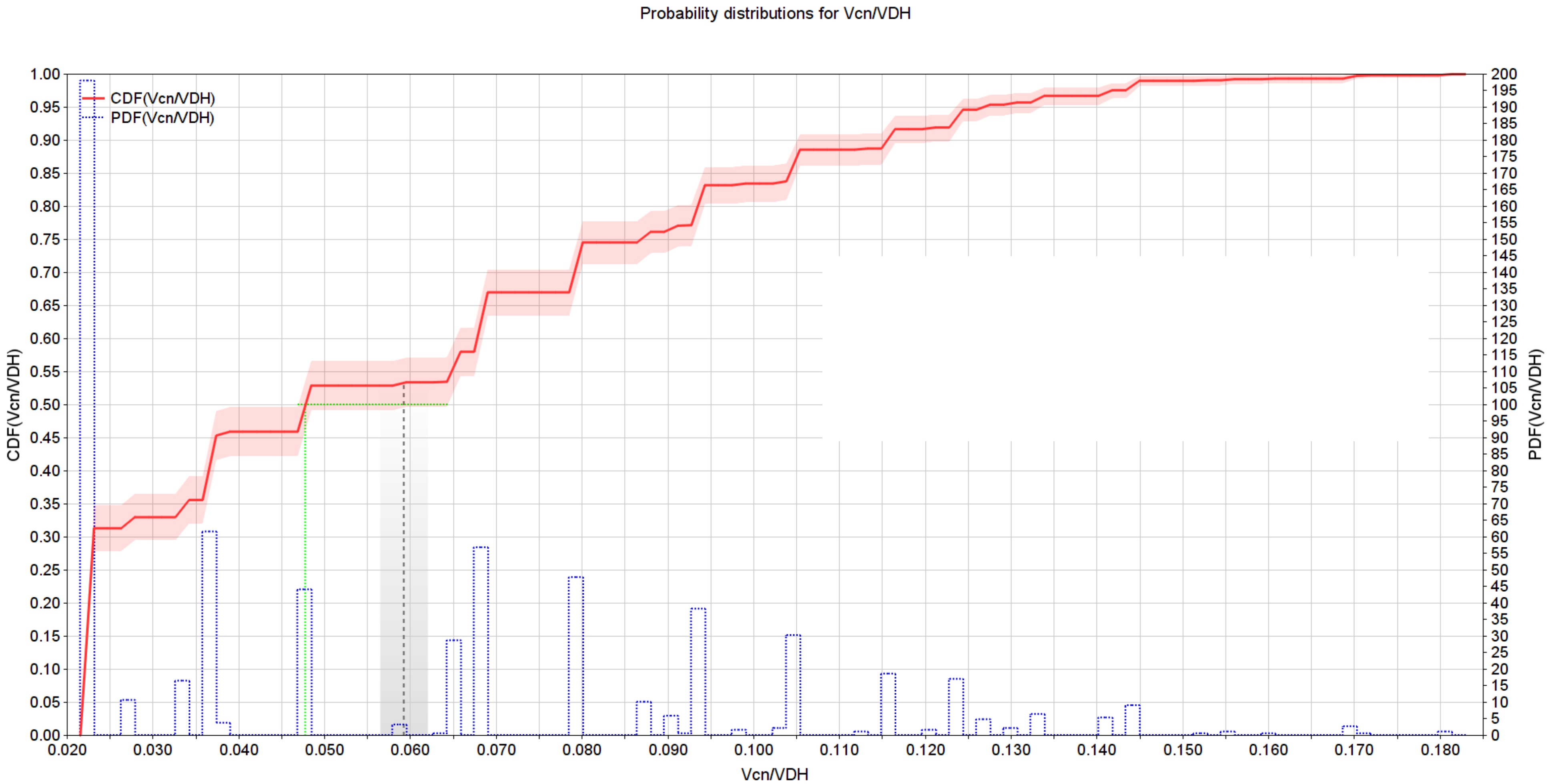

Figure 36 RoPax 1, distribution of probability for the occurrence of ratio Vcn/VDH at sea only.

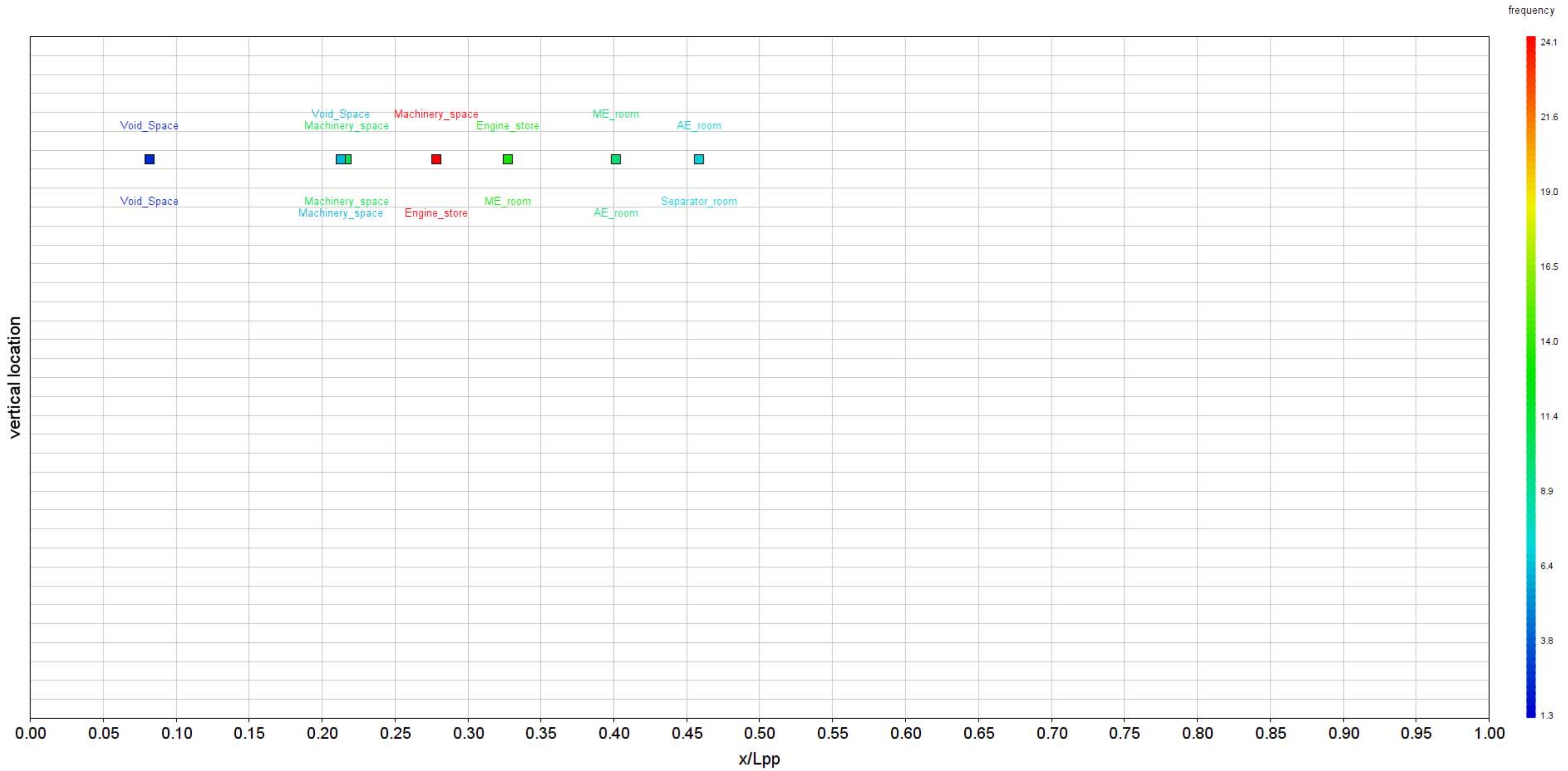

Figure 37 RoPax 1, distribution of frequency (in color) for instances of doors opening at sea only.

The distribution is shown above for longitudinal doors locations. Frequency implies occurrence at any time instance.

RoPax 2

Table 58 List of connected spaces by WTD of RoPax 2.

No	Space 1	Space 2	Class	x/Lbp	y/B	z/draught	% of instances remaining opened (at port and at sea)	% of instances remaining opened (at sea only)
1	Stores	Dry_Provision	C	0.212	-0.065	0.983	31.1	20.1
2	Workshop	Stores	A	0.324	-0.065	0.983	100	100
3	Stab.Room	Workshop	C	0.412	-0.065	0.983	4.1	0.7
4	Stab.Room	Workshop	C	0.529	-0.065	0.983	21.8	5.4
5	Fwrd.Eng.Room	Workshop	C	0.588	-0.065	0.983	33.7	17.7
6	Aft.Eng.Room	Fwrd.Eng.Room	C	0.451	-0.295	0.983	48	22
7	Treat.Pump.Etc	Aft.Eng.Room	C	0.451	0.295	0.983	26.9	7.8

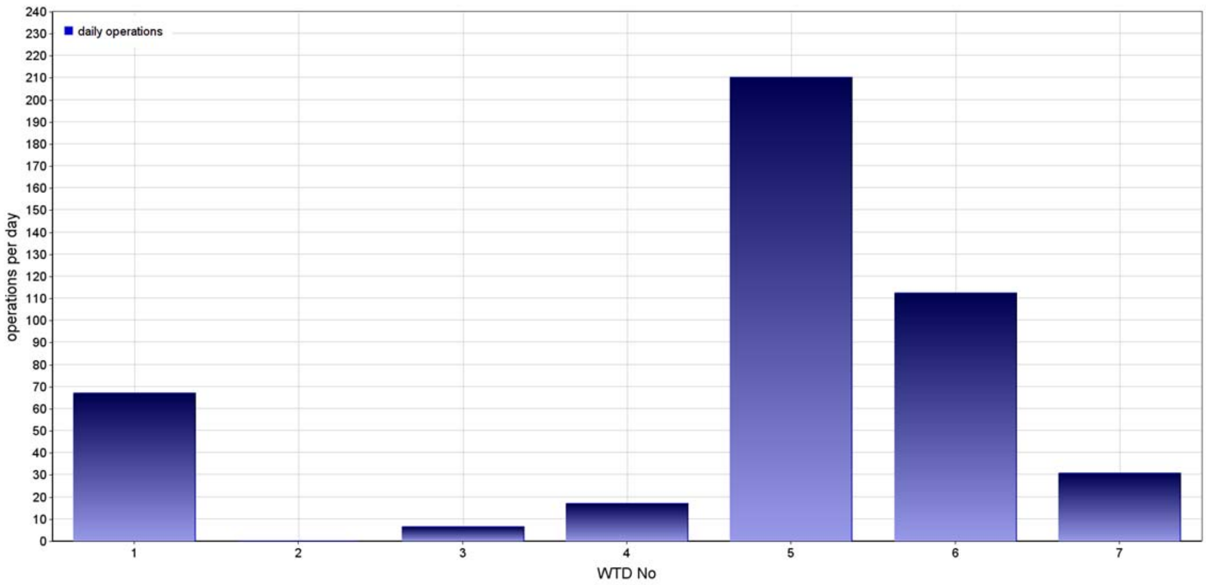

Figure 38 RoPax 2, doors opening or closing operation per day, statistics at sea and in port.

Table 59 RoPax 2 - statistics of operation of combination of doors.

Number of doors opened	% of instances (at port and at sea)	% of instances (at sea)
0	0	0
1	35.65	54.7
2	19.11	26.29
3	15.62	11.2
4	11.77	6.23
5	11.11	1.52
6	4.9	0.06
7	1.85	0

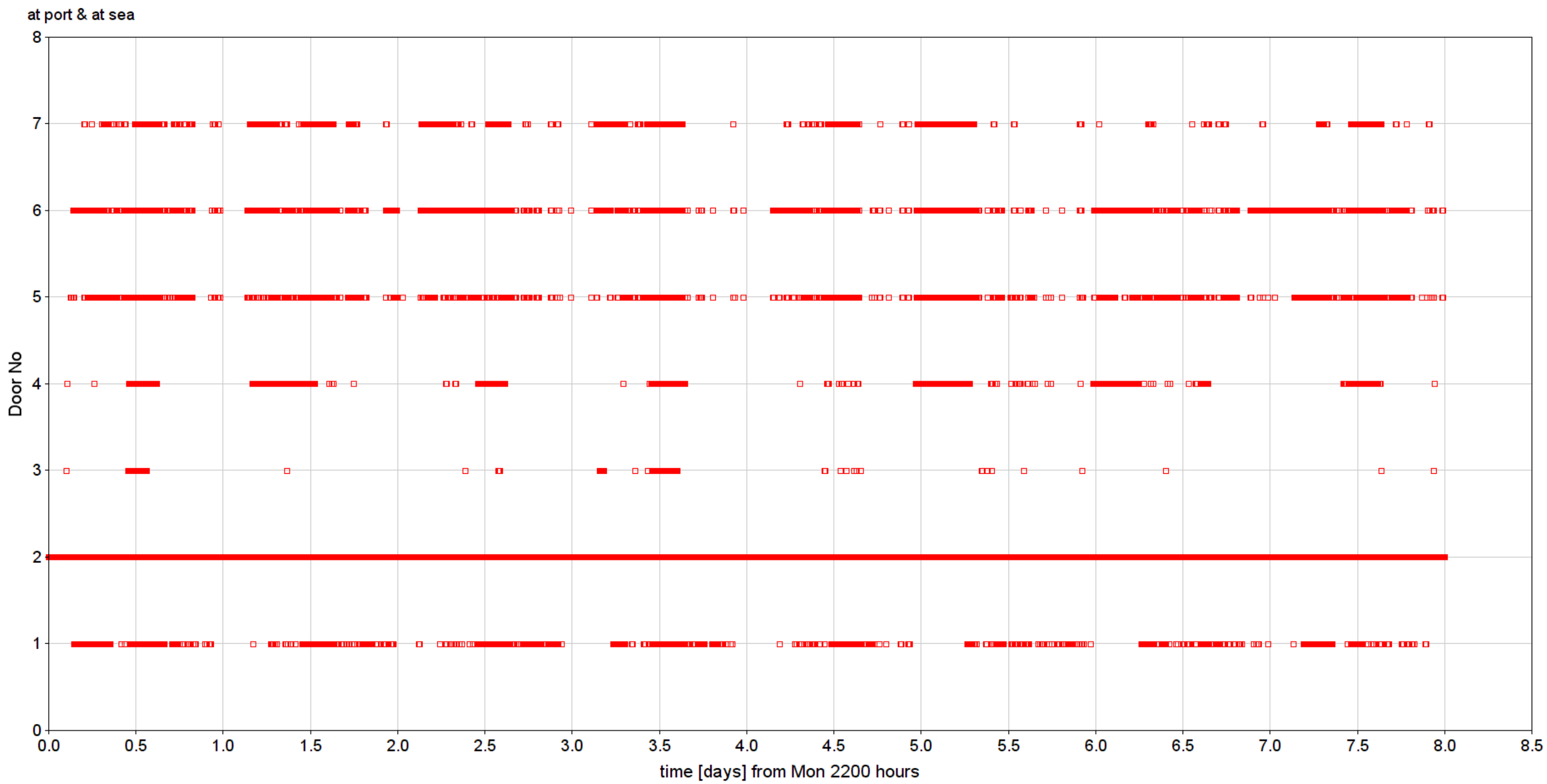

Figure 39 RoPax 2, instances of doors openings at sea and in port.

Every record indicates opened door at one instance in time (the amount of time a door remains opened is not shown).

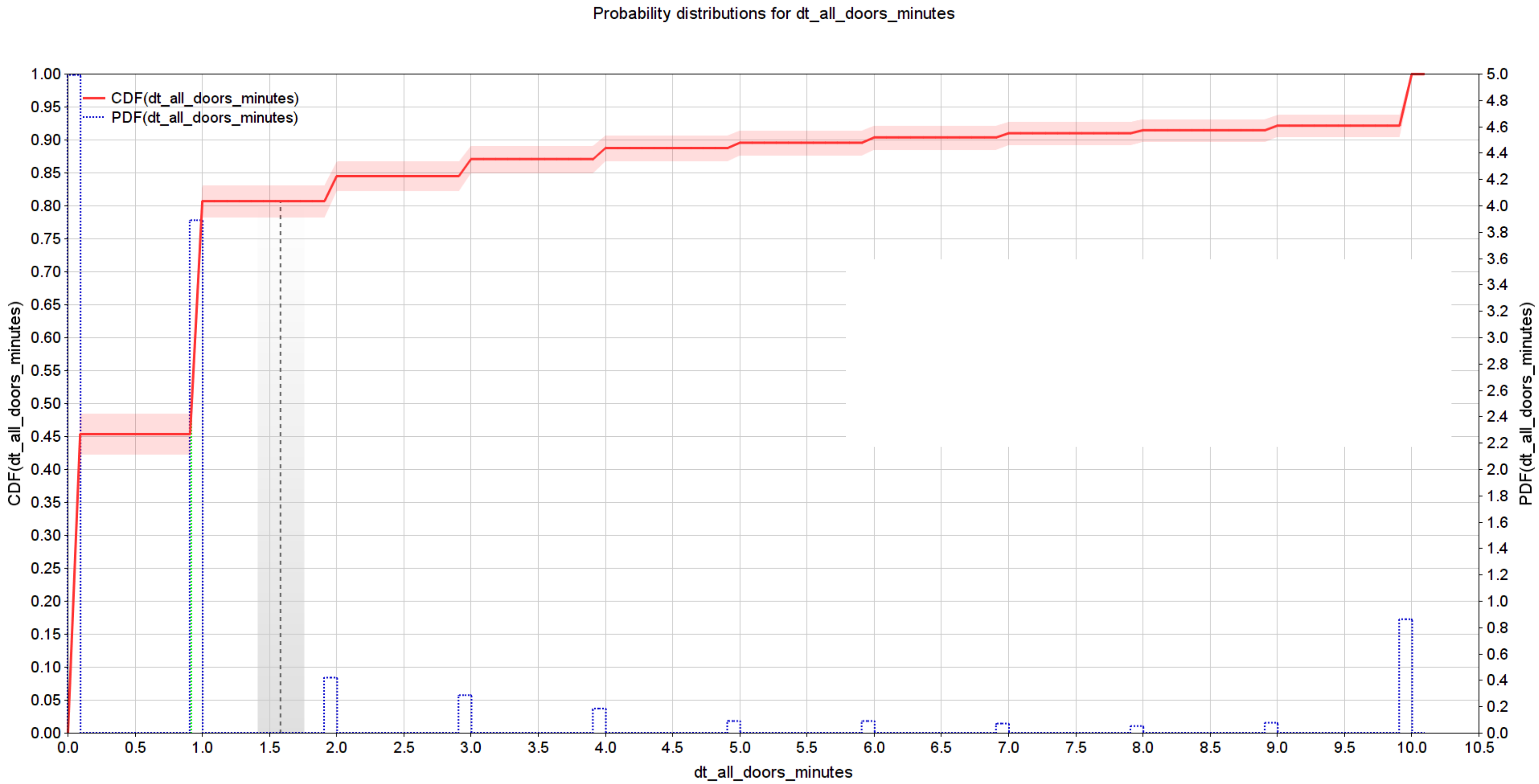

Figure 40 Ropa2, distribution of probability for the duration of opening of WTDs at sea and in port.

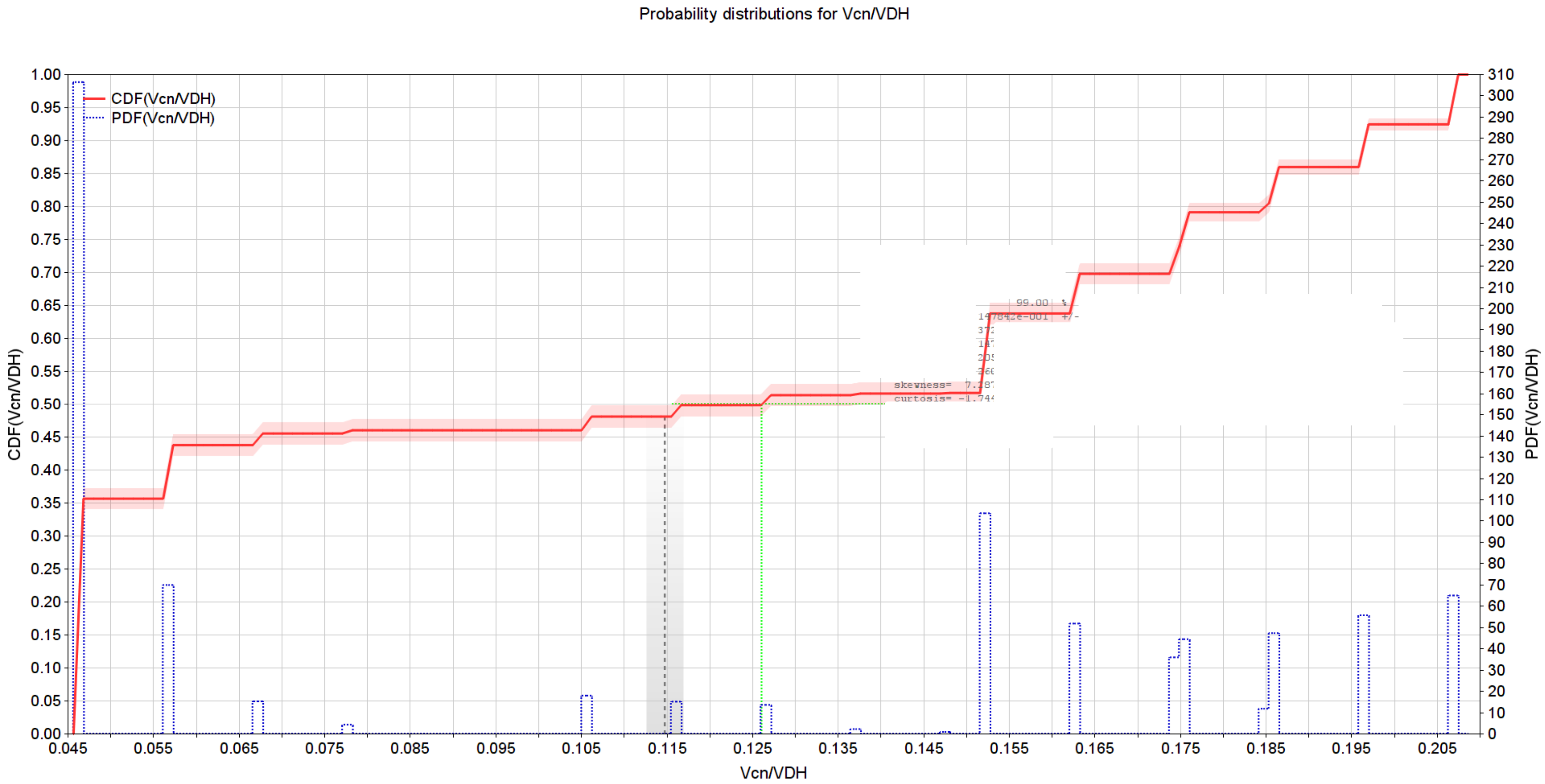

Figure 41 RoPax 2, distribution of probability for the occurrence of ratio Vcn/VDH at sea and in port.

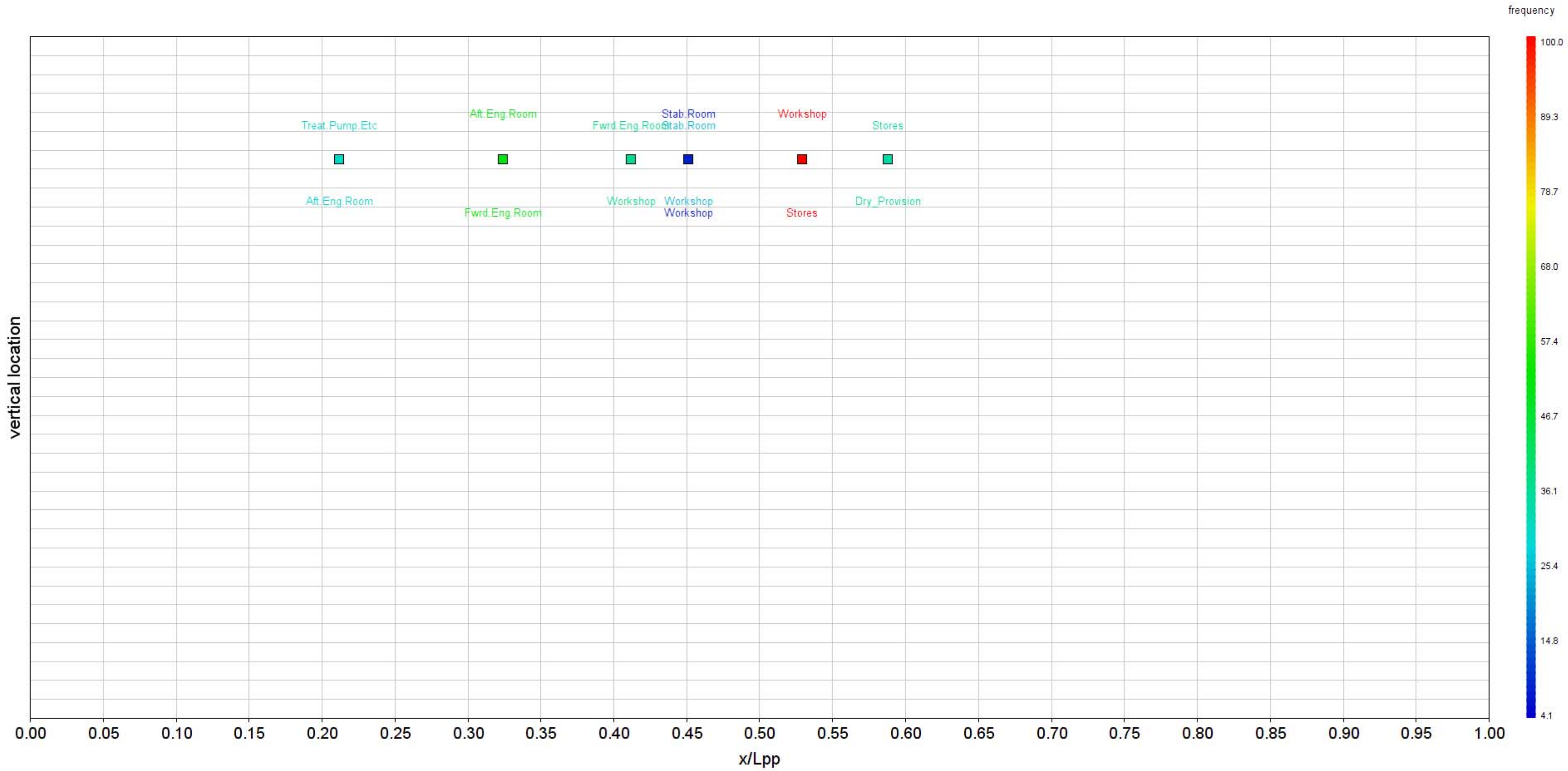

Figure 42 RoPax 2, distribution of frequency (in color) for instances of doors opening at sea and in port.

The distribution is shown above for longitudinal doors locations. Frequency implies occurrence at any time instance.

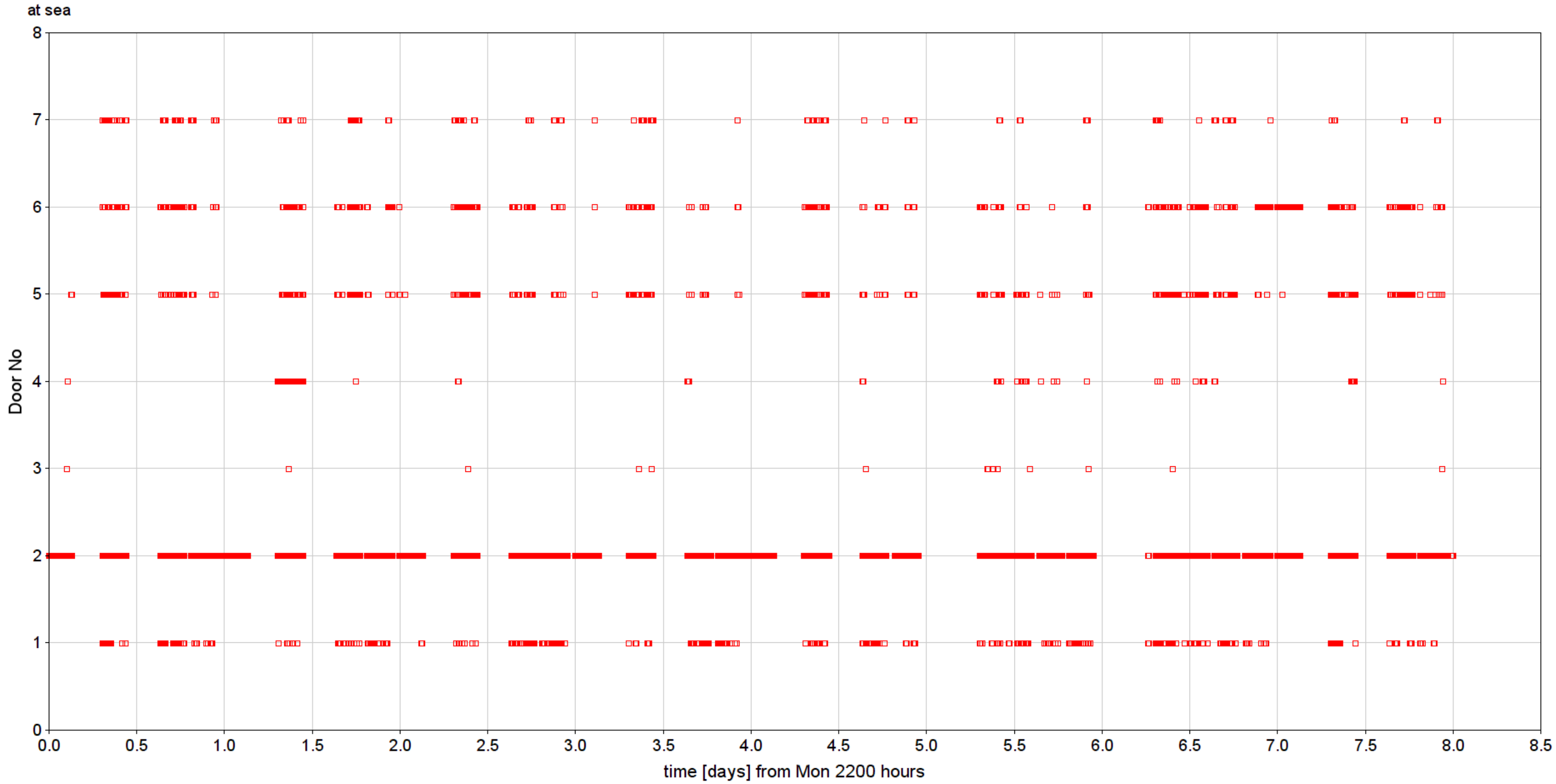

Figure 43 RoPax 2, instances of doors openings at sea only.

Every record indicates opened door at one instance in time (the amount of time a door remains opened is not shown).

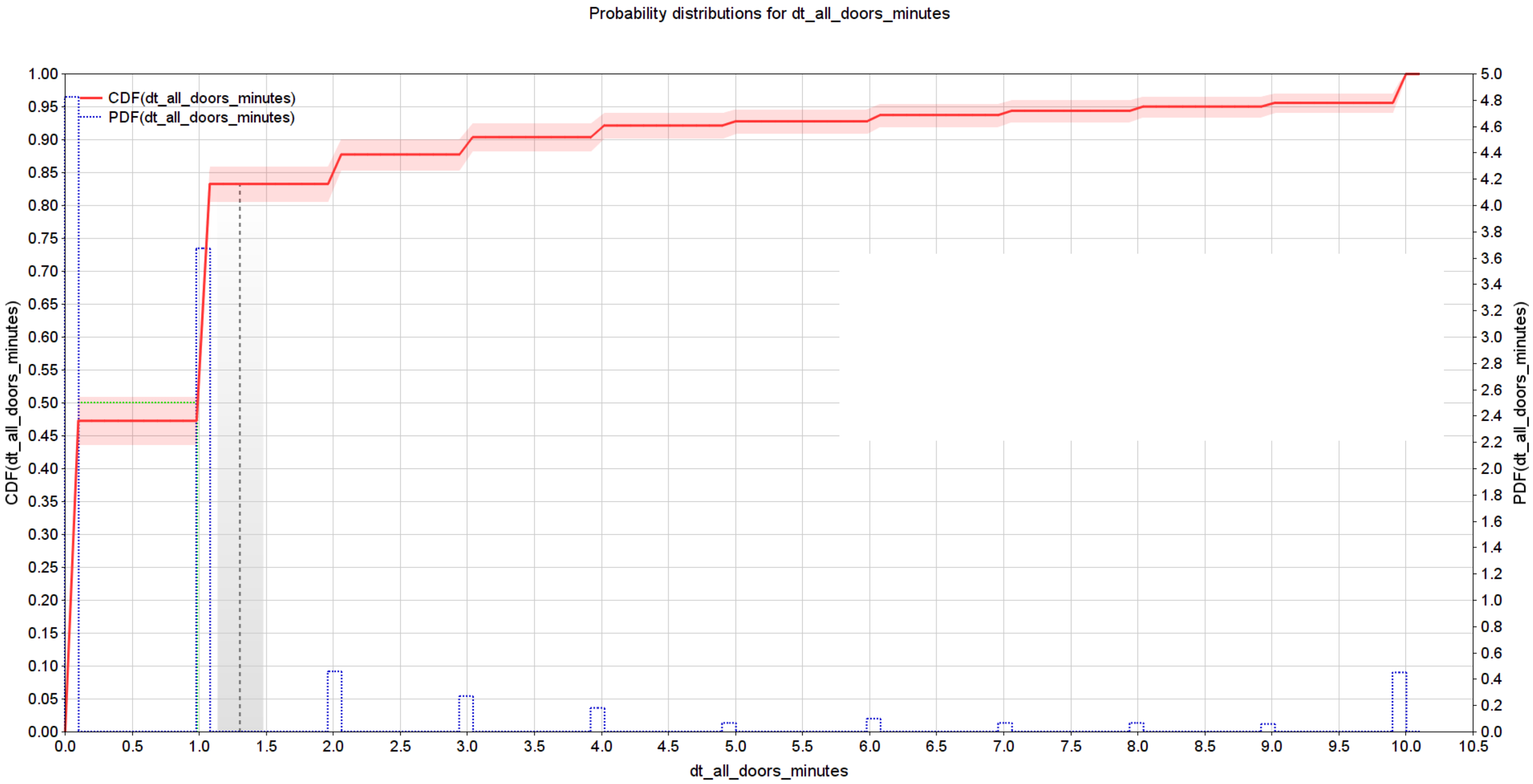

Figure 44 Ropa2, distribution of probability for the duration of opening of WTDs at sea only.

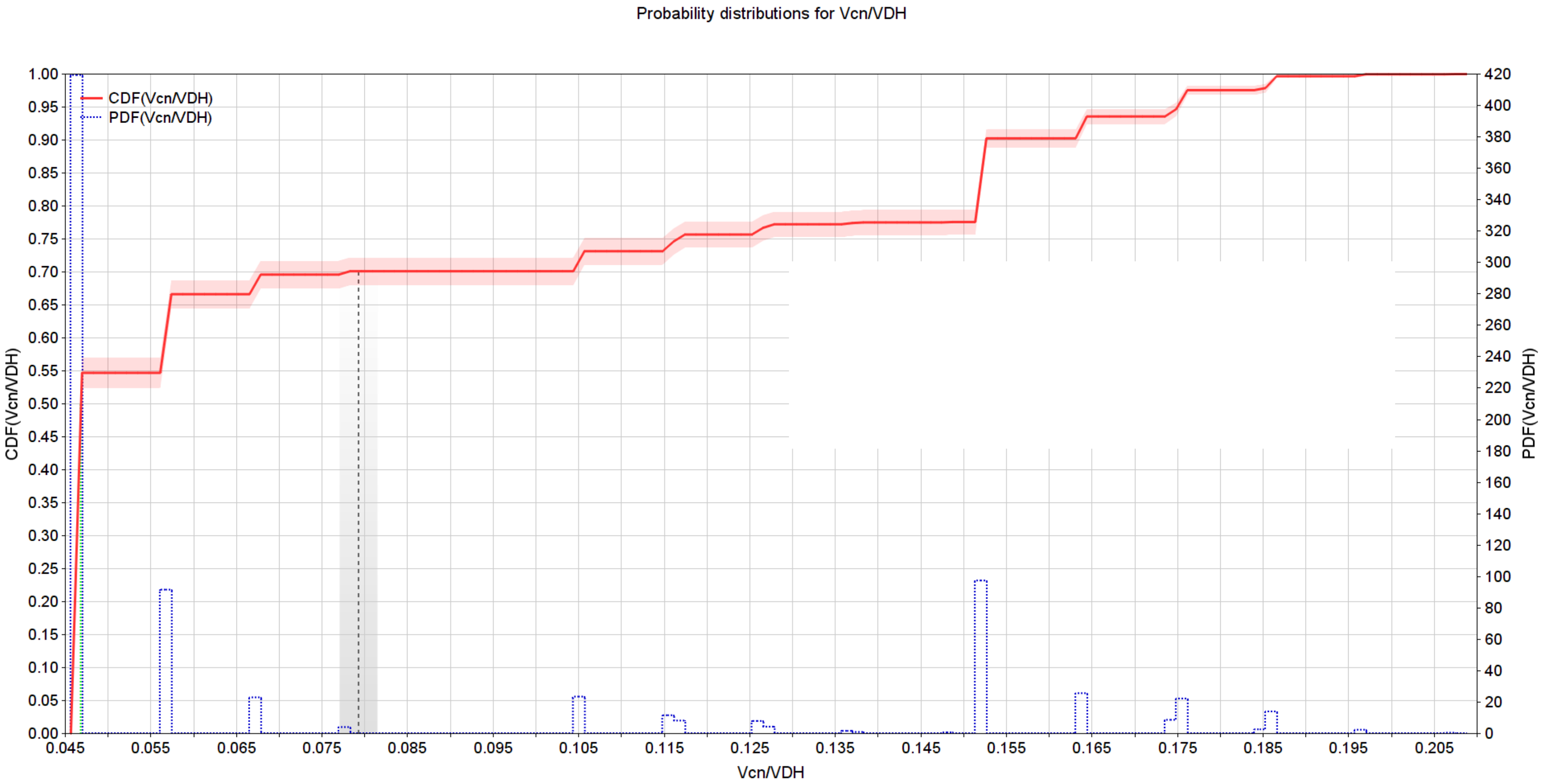

Figure 45 RoPax 2, distribution of probability for the occurrence of ratio Vcn/VDH at sea only.

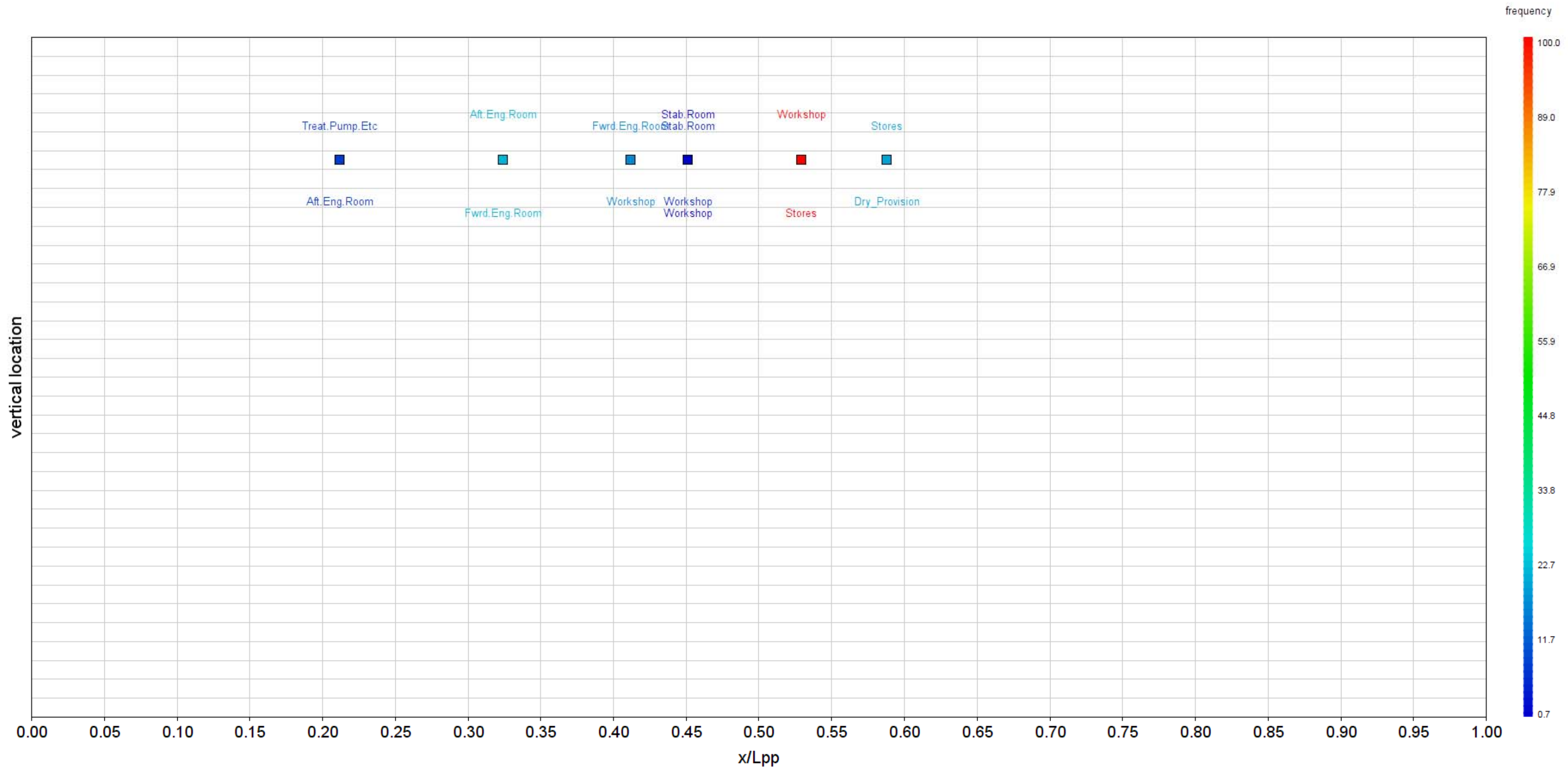

Figure 46 RoPax 2, distribution of frequency (in color) for instances of doors opening at sea only.

The distribution is shown above for longitudinal doors locations. Frequency implies occurrence at any time instance.

Appendix 2 Vulnerability assessment

Based on information collected, as presented in **Appendix 1**, an exercise of risk quantification has been performed.

Methodology of [15], also explained in [8], has been used to calculate instantaneous vulnerability (probability to capsize in given sea state, loading conditions and “at this instant” doors status, with no crew action of closing considered). The methodology is based on formulations of Regulation 7 of [22], with the factor “s” of Regulation 7-2 replaced by equation (7). The methodology allows accommodating for the impact of the sea state. The method uses the same flooding cases as set for SOLAS2009 calculations. When doors are opened the extent of flooding is modified accordingly.

$$s_{i,j,k} = \int_0^\infty dHs \cdot f_{Hs|coll}(Hs) \cdot F_{surv}\left(t_0 \middle| d_{i,k}, T_j, Hs\right) \qquad (7)$$

Where $f_{Hs|coll}(Hs)$ is probability density distribution for sea states expected to be encountered during a collision incident, resulting in flooding extent $d_{i,k}$ (flooding case “*i*” involving spaces up to horizontal subdivision “*k*”) whilst the ship operated at draught T_j. The probability of survival, $F_{surv}\left(t_0 \middle| d_{i,k}, T_j, Hs\right)$, for given time t_0 and at given flooding case $d_{i,k}$, draught T_j and sea state Hs, has been approximated with model (8):

$$F_{surv}\left(t \middle| d_{i,k}, T_j, Hs\right) = \left[1 - \Phi\left(\frac{Hs - H_{crit,i,j,k}}{0.039 \cdot H_{crit,i,j,k} + 0.049}\right)\right]^{\frac{t}{t_0}} \qquad (8)$$

Where $\Phi(z)$ is the cumulative standard normal probability distribution function.

$H_{crit,i}$ is the 50th percentile significant wave height in which a ship subjected to flooding scenario case d_i might capsize within $t = 30$ minutes, approximated according to (9).

$t_0 = 30\,\text{min}$ is the benchmark physical testing time.

$$H_{crit,i,j,k} = 4 \cdot \left(\frac{GZ_{\max,i,j,k}}{0.12} \cdot \frac{Rnage_{i,j,k}}{16} \right) \quad (9)$$

The calculations were applied for only final stages of flooding and for loading conditions that were recorded on board at the instants of recording of the WTD status, as well as for loading conditions DS, as implied by Regulation 7.1. An in-house software PROTEUS3 of Safety At Sea has been used for the purpose of calculations.

The methodology was also applied and calculated by the designers and the yards with the use of commercial naval architecture packages NAPA, with the index "s" calculated according to Regulation 7-2, for final stage of flooding but loading conditions DS, as implied by Regulation 7.1.

Thus calculated index has been designated as A*. An index calculated for all doors closed has been designated as A*closed, whereas index calculated for cases with opened doors has been designated as A*opened.

For investigation of the impact of the sea state, the survival factor "s" was replaced directly by equation (8). In these cases the index A is referred to as "equivalent A".

The calculations and analyses are presented in Figure 48 to Figure 3. Figure 47 presents with a validation case of the technique to calculate GZ stability curve for the extent of flooding affected by non-closure of WTD determined numerically.

The most significant observation is that the impact of any one single door, while varying from door to door, is small relative to the impact of a combination of doors left opened.

It appears that there is no identifiable trend in use of specific combination of doors. This may be understandable given the number of combinations increases very rapidly with increasing number of doors, as shown in Table 60.

Based on Figure 49, Figure 52 and Figure 54, showing relationship between frequency of doors opening and the impact on reduction of index A, it may be stated that frequency of usage of any particular door is not related to impact such door has on stability. Some of the most frequently used doors have some of the biggest impact on stability at the same time. This indicates possible inconsistency in policies of permitting usage of these doors.

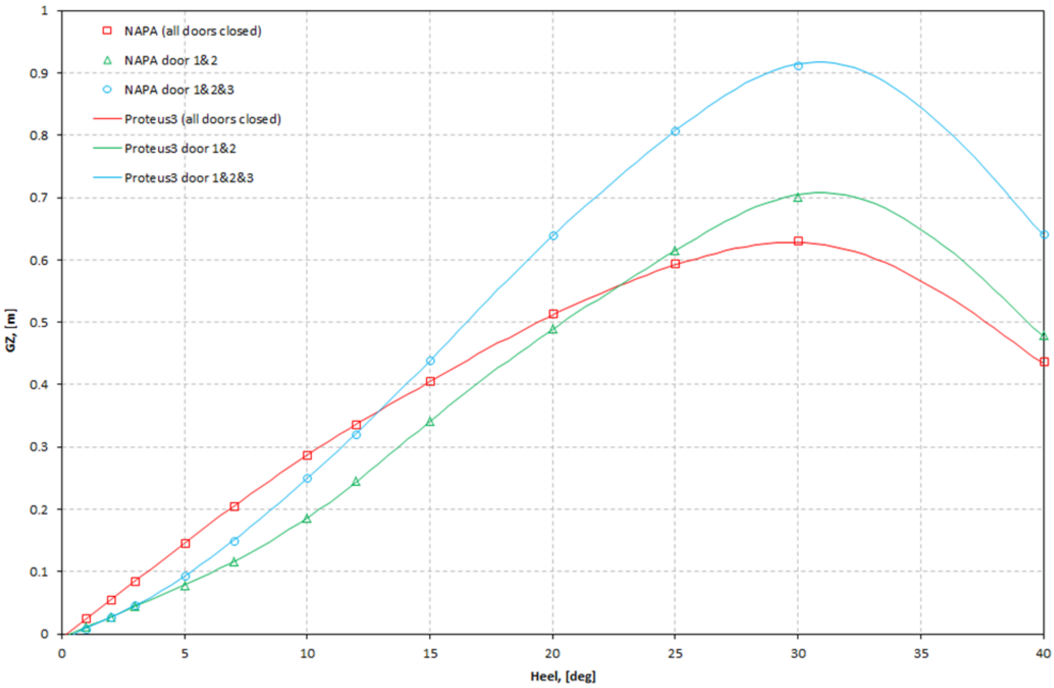

Figure 47 Elements of cross-validation.

The above picture serves as an example of checking consistency of different software packages, of NAPA and PROTEUS3, both applying the same methodology for accounting for impact of opened WTD on stability. Both sets of tools establish numerically the relevant extent of flooding for every combination of set of doors assumed as opened.

Table 60 Impact of number of WTD on number of combinations of doors states.

Door No	NoCombinations
1	2
2	4
3	8
4	16
5	32
6	64
7	128
8	256
9	512
10	1,024
11	2,048
12	4,096
13	8,192
14	16,384
15	32,768
20	1,048,576
25	33,554,432
30	1,073,741,824
35	34,359,738,368
40	1,099,511,627,776
45	35,184,372,088,832
50	1,125,899,906,842,620
55	36,028,797,018,964,000

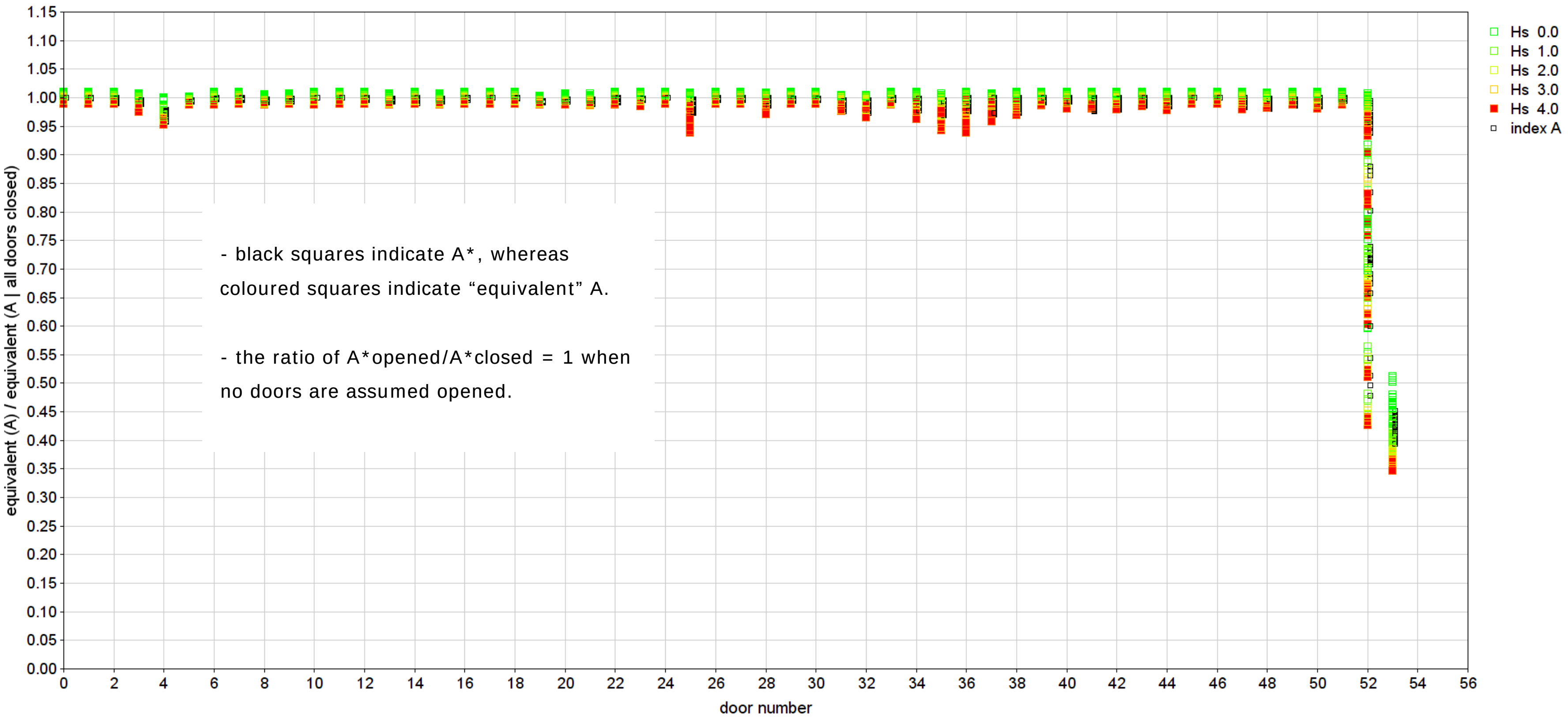

Figure 48 Vulnerability calculations Cruise 1, 51 doors.

Calculation of “equivalent A”, with s factor according to (7), for loading condition as recorded. The door number “0” corresponds to all doors closed. Case 52 corresponds to actual combination of doors recorded, and case 53 considers all doors opened.

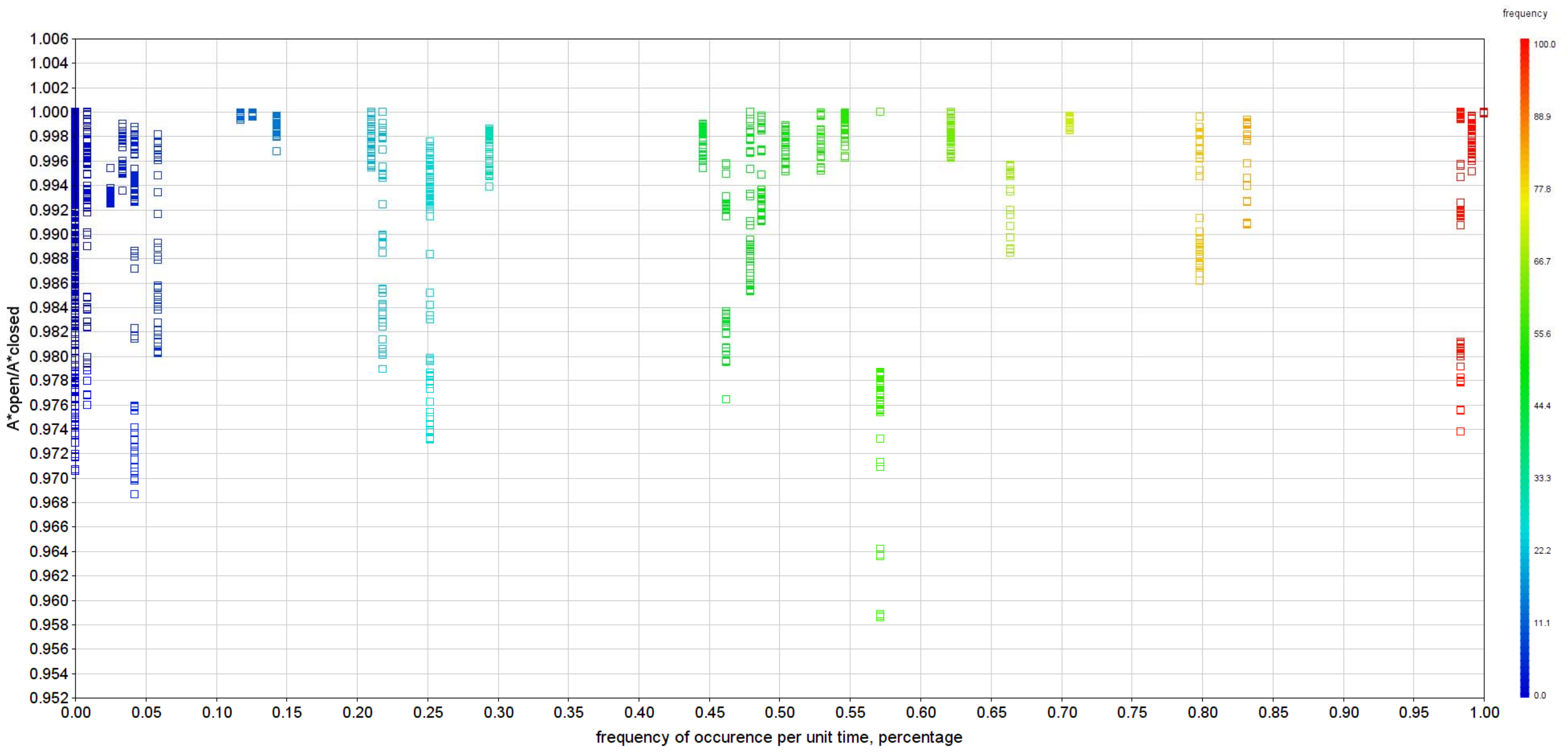

Figure 49 Cruise 1, relationship between frequency of doors opening and the impact on reduction of index A.

Calculation for a range of loading conditions as recorded. Frequency implies occurrence of opening per every instance recorded over two weeks and at two hours intervalls.

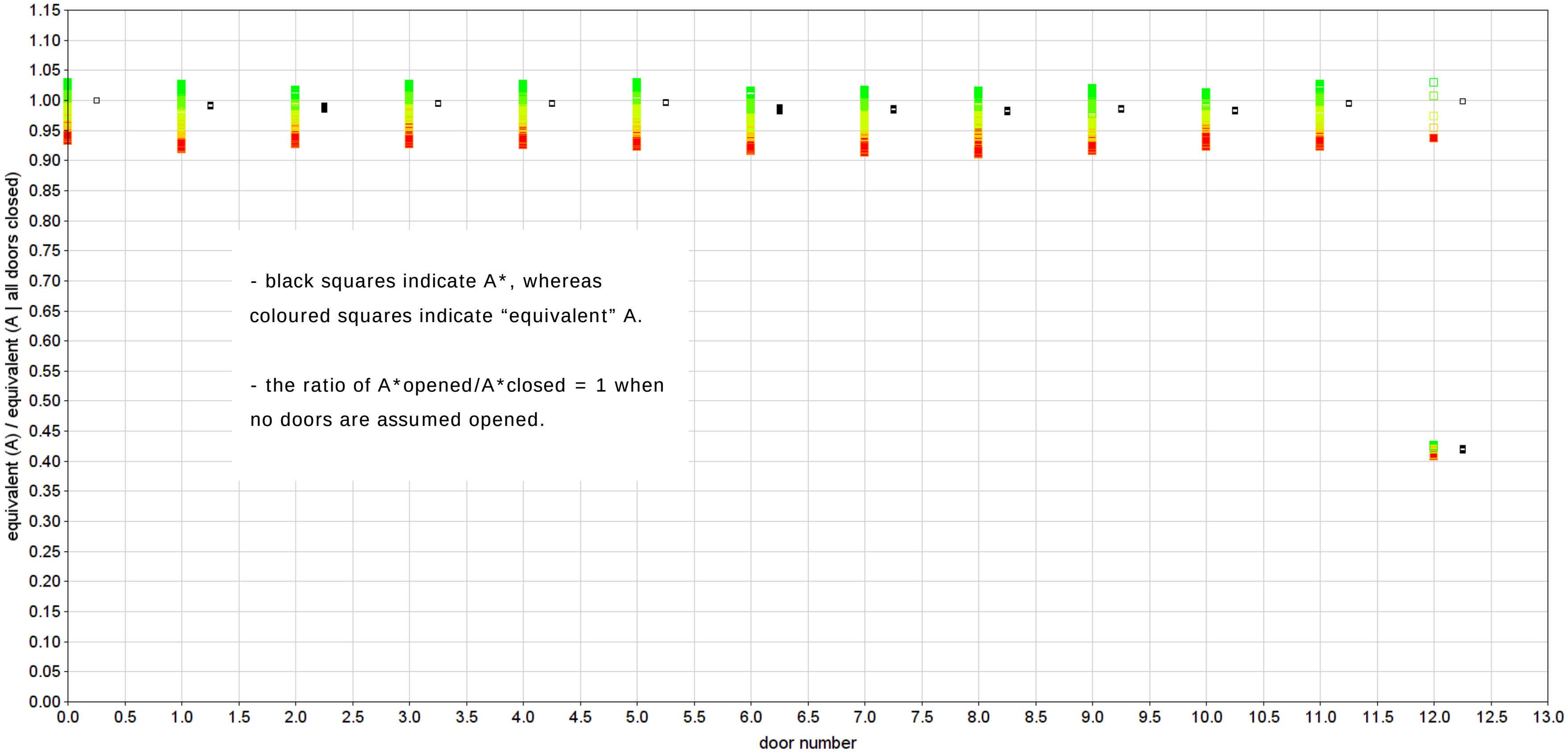

Figure 50 Vulnerability calculations Cruise 2.

Calculation of "equivalent A", with s factor according to (7), for loading condition as recorded. The door number "0" corresponds to all doors closed. Case considering all doors opened plotted under results in case 12.

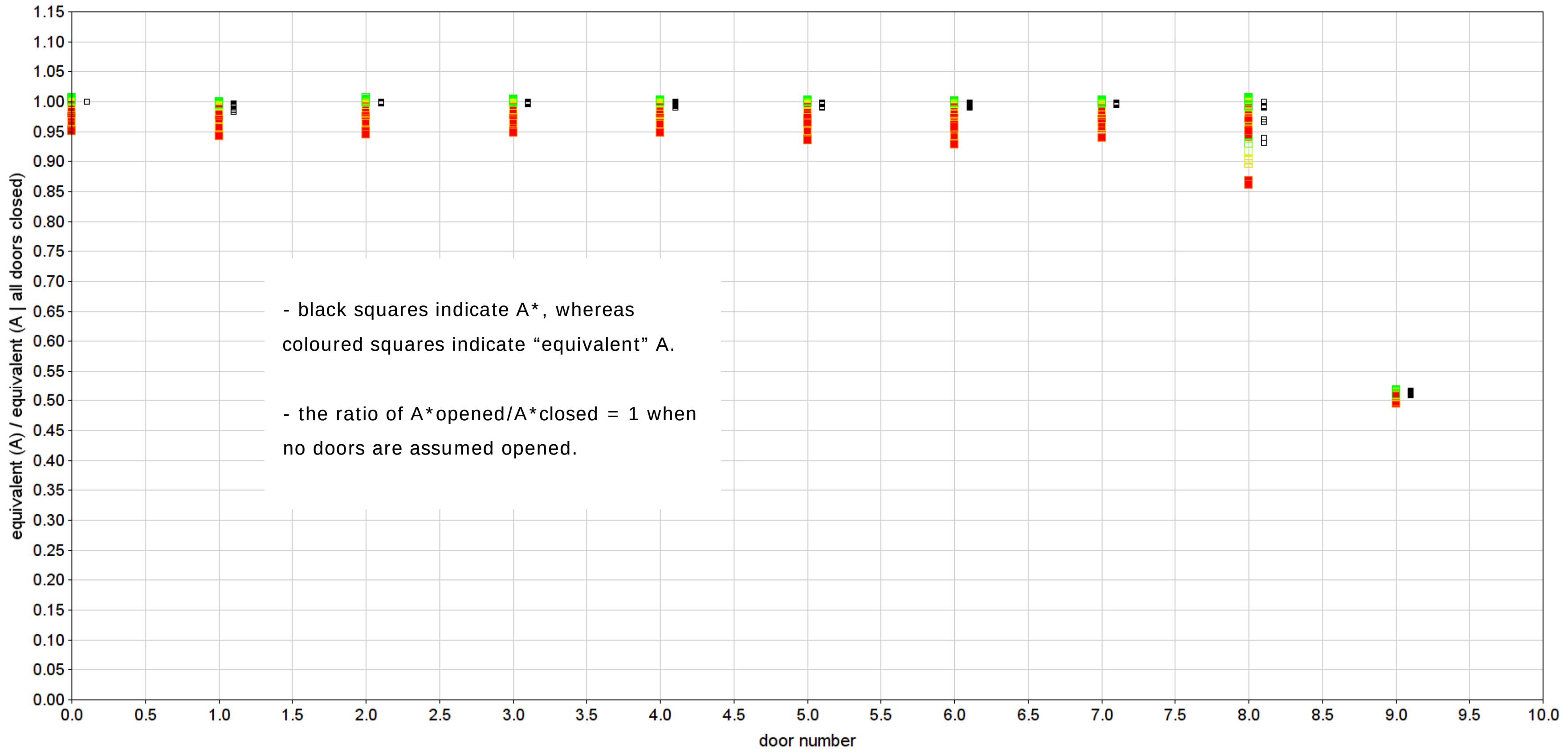

Figure 51 Vulnerability calculations RoPax 1. 7 doors.

Calculation of "equivalent A" , with s factor according to (7), for loading condition as recorded. The door number "0" corresponds to all doors closed. Case 8 corresponds to actual combination of doors recorded, and case 9 considers all doors opened.

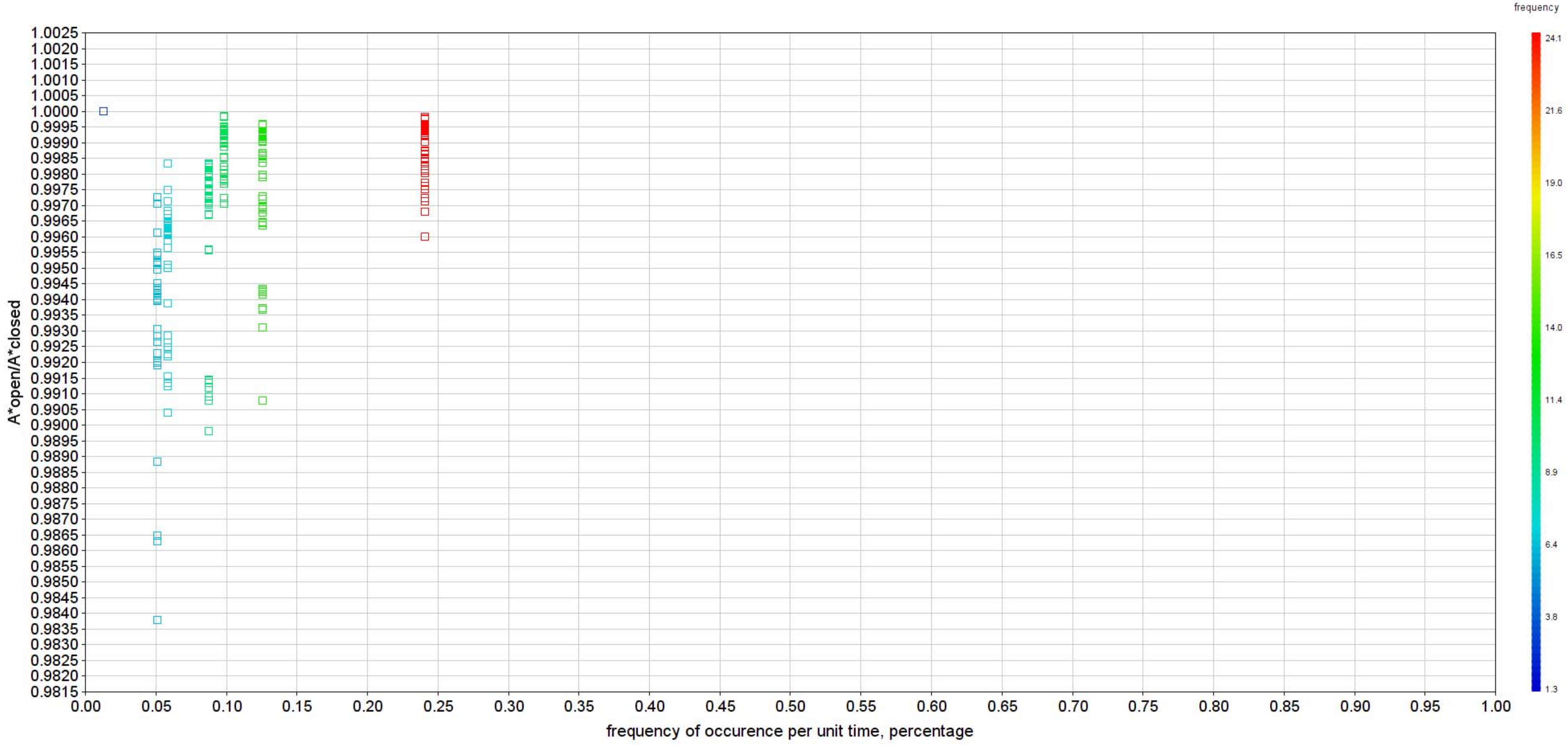

Figure 52 RoPax 1, relationship between frequency of doors opening and the impact on reduction of index A.

Calculations at loading conditions as recorded. Frequency implies occurrence per one minute intervalls.

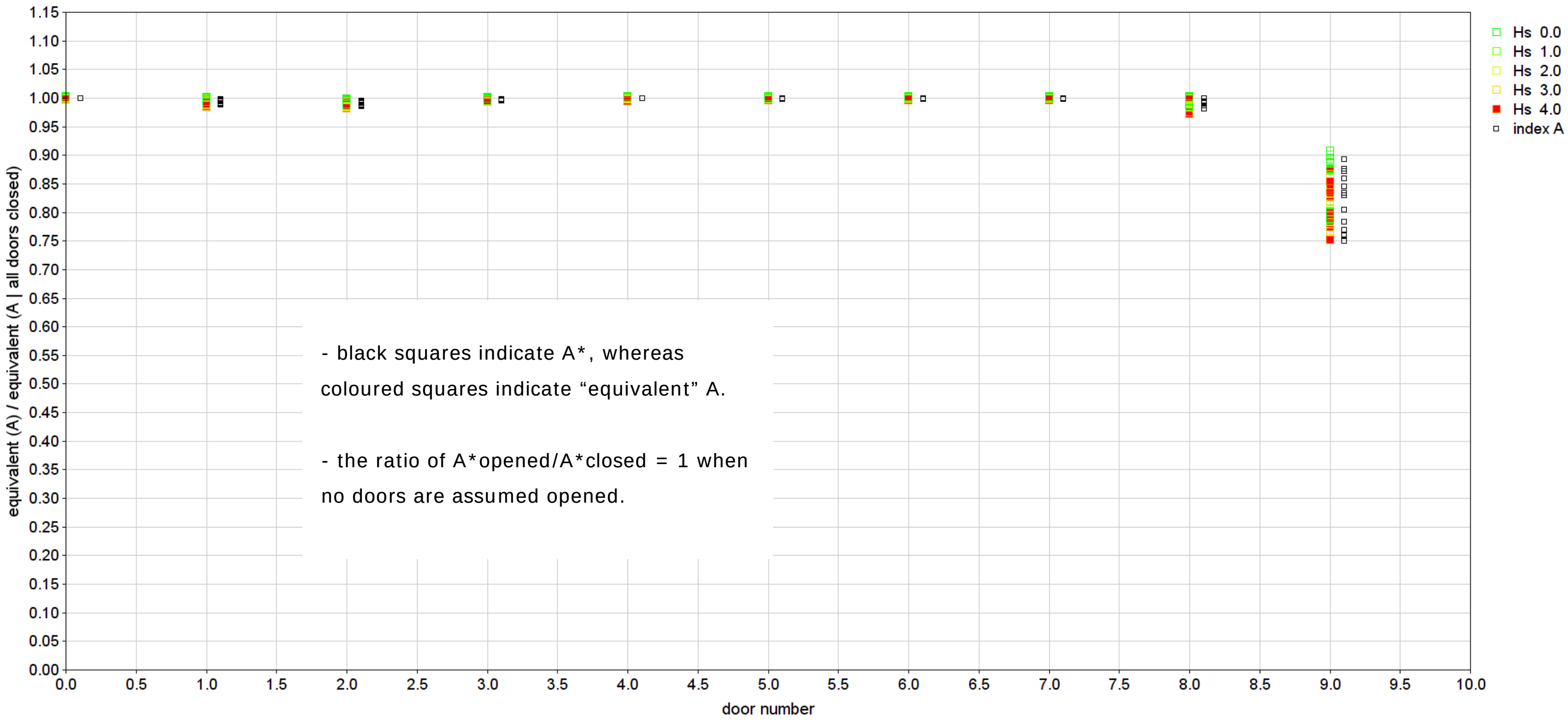

Figure 53 Vulnerability calculations RoPax 2. 7 doors.

Calculation of “equivalent A” , with s factor according to (7), for loading condition as recorded. The door number “0” corresponds to all doors closed. Case 8 corresponds to actual combination of doors recorded, and case 9 considers all doors opened.

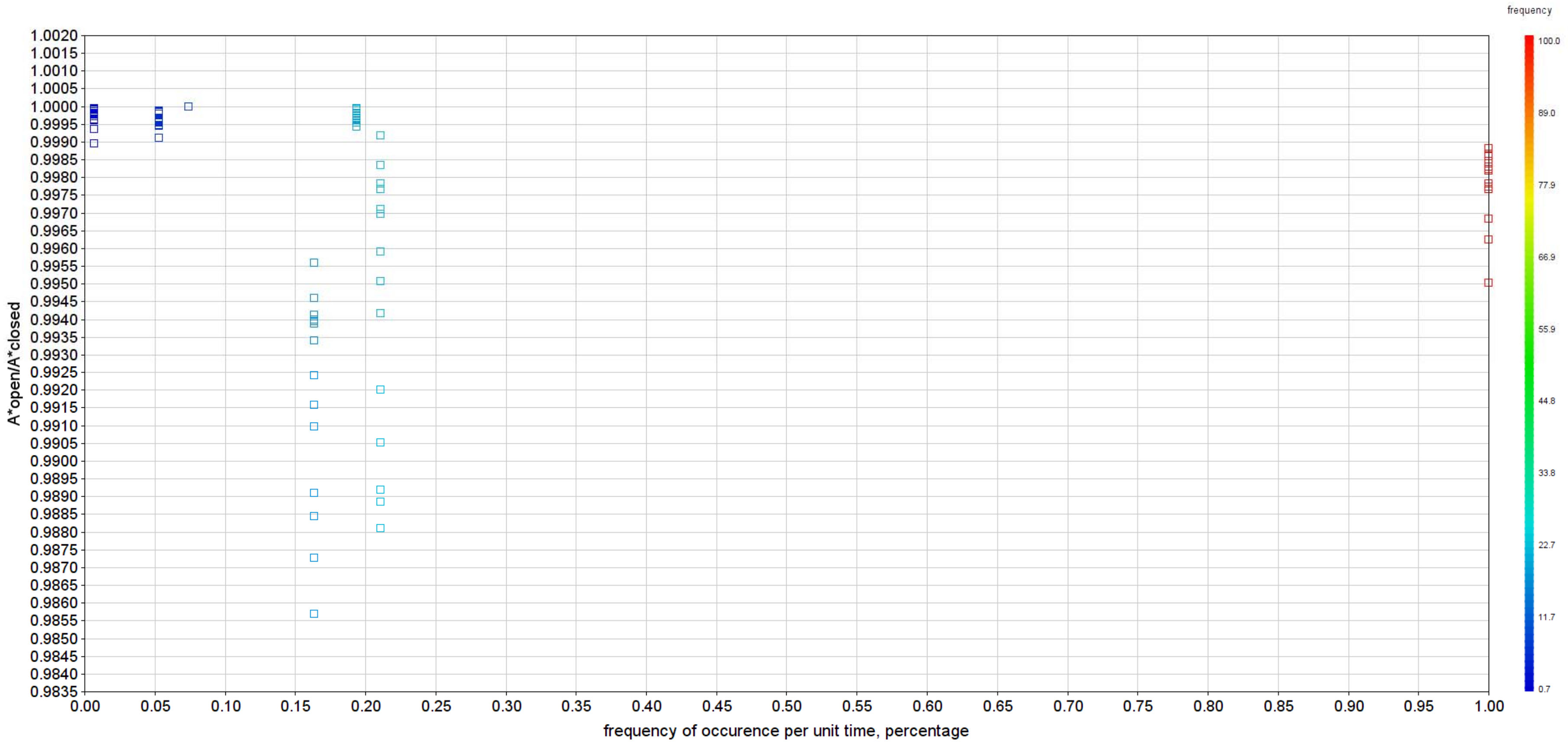

Figure 54 RoPax 2, relationship between frequency of doors opening and the impact on reduction of index A.

Calculations at loading conditions as recorded. Frequency implies occurrence per one minute intervalls.

Furthermore, according to stated objectives of the project a series of calculations to identify the worst impact set of doors have been performed by all project participants. Calculations are shown in Figure 55 to Figure 59.

The methodology used for the assessment of survivability is the simplified method to calculate the attained index as proposed by CLIA in MSC93/6/8, [21]. The methodology was developed among the members of cruise ship forum, however, it is generic and applicable for other ship types.

The simplified index A* is based on the procedures as described in SOLAS II-1, however only the final stage of flooding is calculated. In this study the index is calculated for the deepest subdivisions draught d_s only.

Following calculations have been carried out:

1. Simplified index A* for all doors closed
2. Index A* for any single WTD open
3. Index A* for a number of random combinations of open WTD

The calculations have been carried out with NAPA. The effect of an open WTD has been accounted for by defining the door as opening with the type WEPROGRESSIVE and using the calculation option WEPROGR.

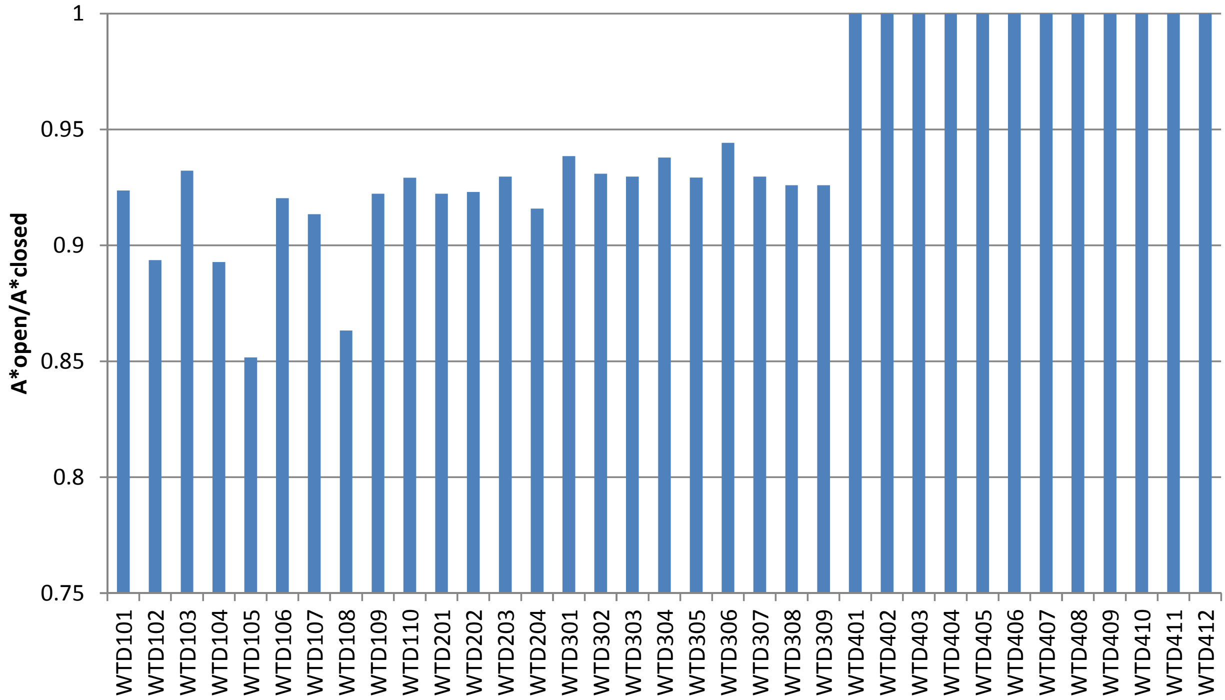

Figure 55 LARGE CRUISE, impact of single WTD doors.

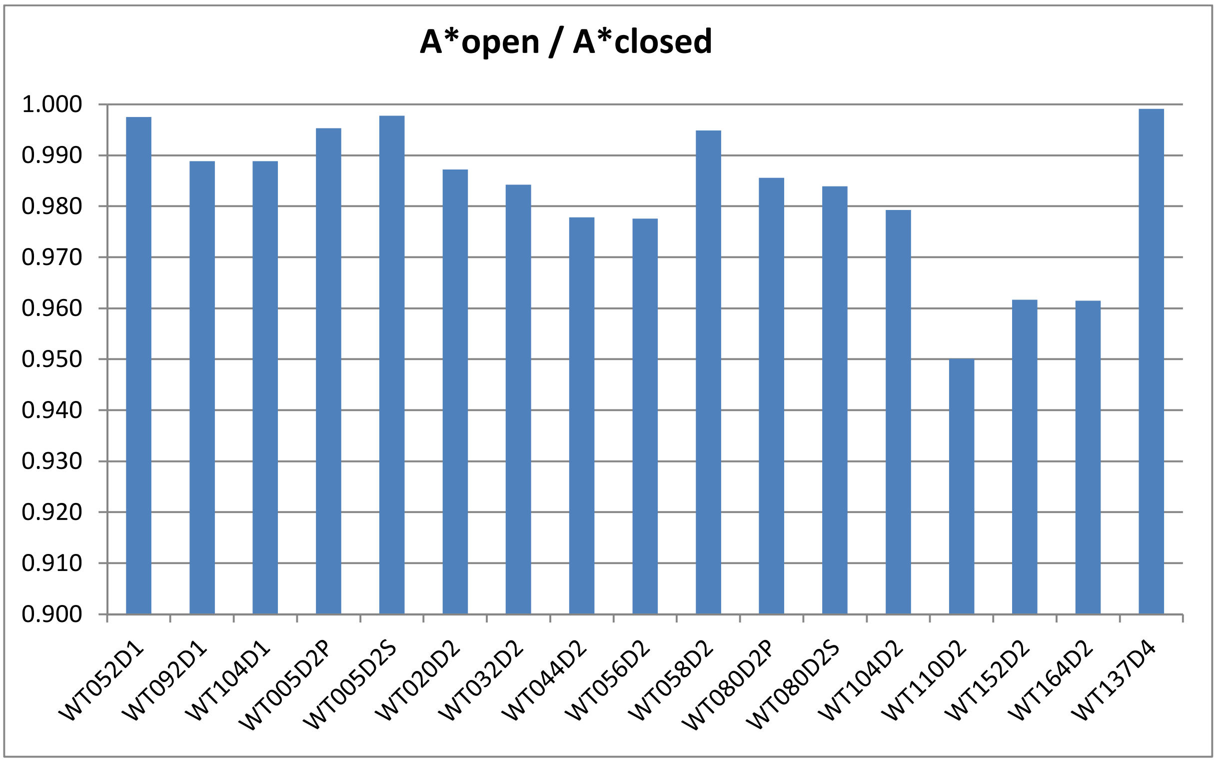

Figure 56 MEDITERRANEAN ROPAX, impact of single WTD doors.

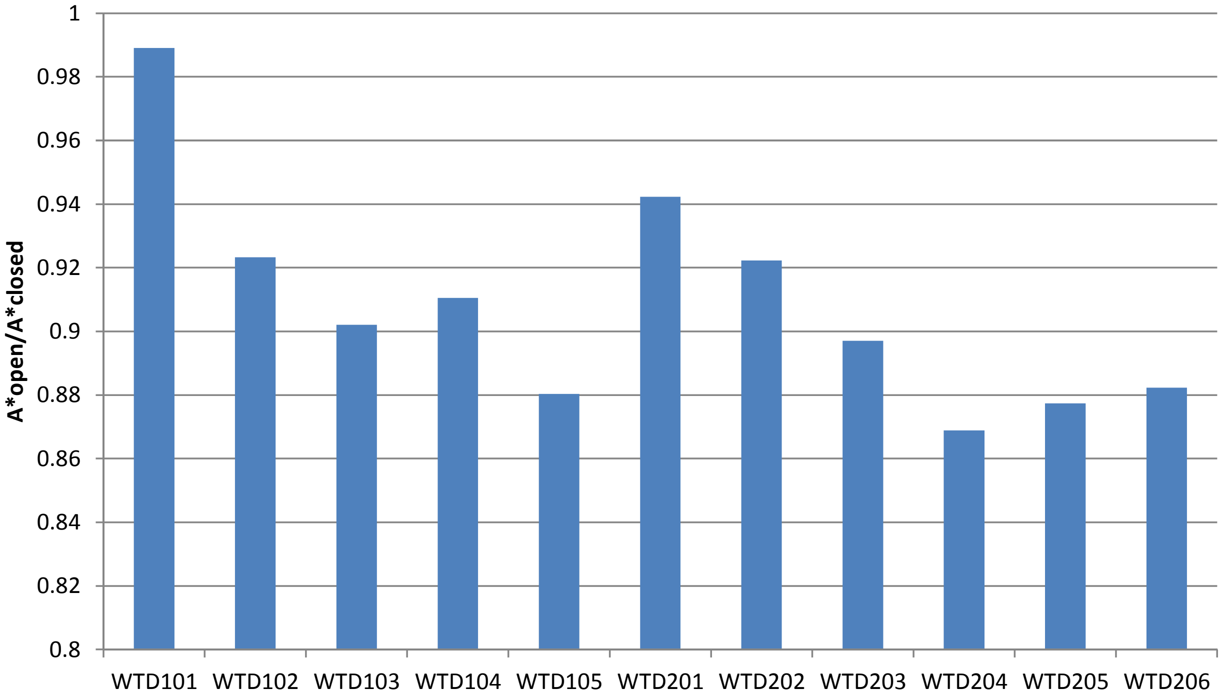

Figure 57 SMALL CRUISE, impact of single WTD doors.

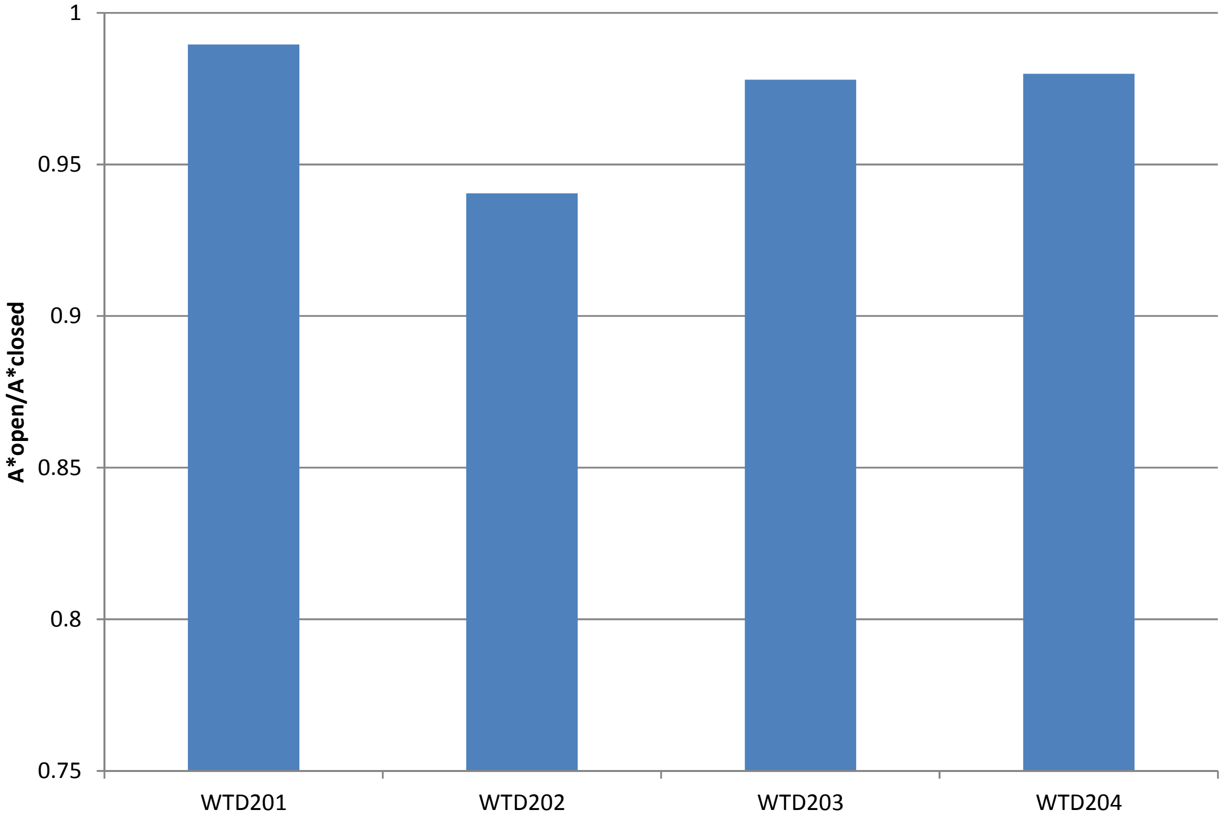

Figure 58 SMALL ROPAX, impact of single WTD doors.

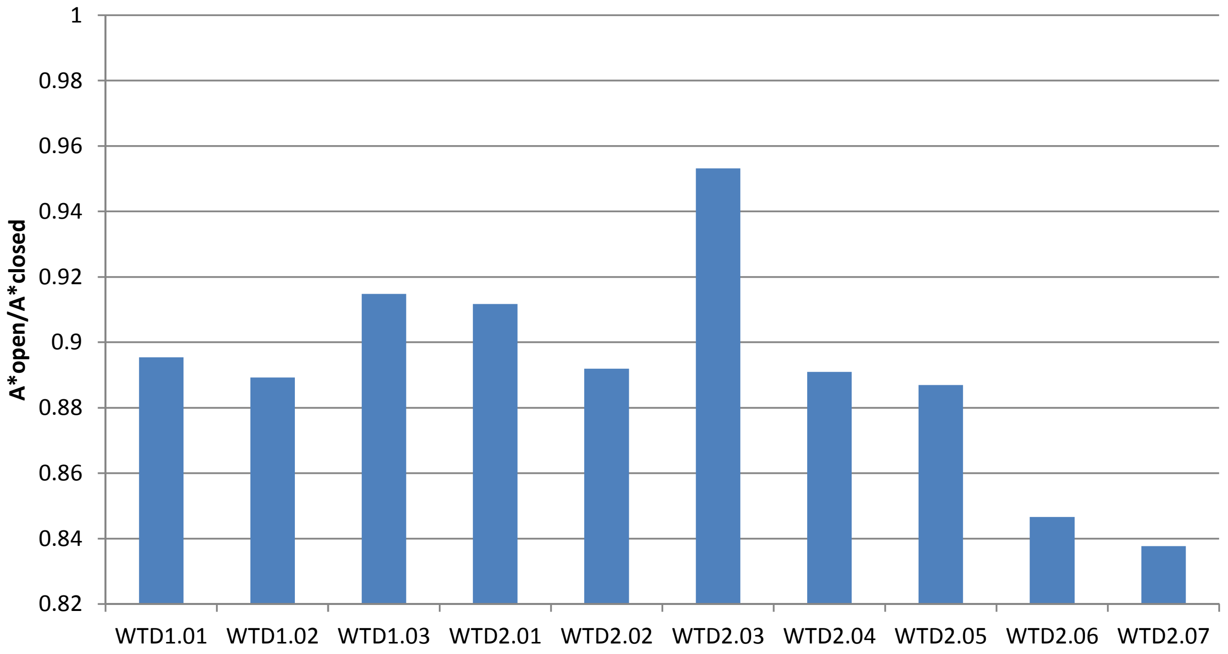

Figure 59 BALTIC ROPAX, Impact of single WTD doors.

Appendix 3 Crew actions

To assess impact of crew actions one of the RoPax ships has been used for study of the reduction of risks due to the action of crew in closing doors within estimated response time frame (up to 30 minutes) for all doors closures.

This study comprised numerical time-domain simulations of ship response to damages in a Monte Carlo fashion and based on algorithms of [7], with a series of damages sampled from statistical information on collision characteristics.

The simulation for each of damages was performed for 30 minutes (reflecting assumptions of SOLAS2009) real time frame to determine capsize or survival within the simulation time. The time to close the doors has been used as variable. A probability has been assigned according to observed frequency of capsizes, for all scenarios.

The results are then presented as a ratio of complement to the cumulative probability to capsize within simulation time of 30minutes for cases with WTD closed within given time "t", $1 - cdf_{ttc}(30min|WTD\ closed\ in\ time\ t)$ and cases where WTD were closed, $1 - cdf_{ttc}(30min|WTD\ closed)$, as given by equation (10) and shown in Figure 60.

$$r(t) = \frac{1 - cdf_{ttc}(30min|WTD\ closed\ in\ time\ t)}{1 - cdf_{ttc}(30min|WTD\ closed\ )} \qquad (10)$$

Based on the results for cases of all doors closed, WTD closed in 2 minutes, 5 minutes, 7.5 minutes, 10 minutes, 15 minutes, 20 minutes and 30 minutes, a reduction factor $c(t)$ of the impact of opening of the WTD has been fitted as given by (11) and shown in Figure 61.

$$c(t) = 1.047 \cdot \left(1 - e^{-0.104 \cdot t}\right) \qquad (11)$$

The longer it takes doors to close, the higher is the percentage of total risk contribution due to additional flooding extent due to opening of WTD. If doors are closed in 30 minutes after instant of hull breach, the risk remains as if the doors were not closed at all. If WTD close in 0 minutes, then the survivability remains as if the doors were never opened.

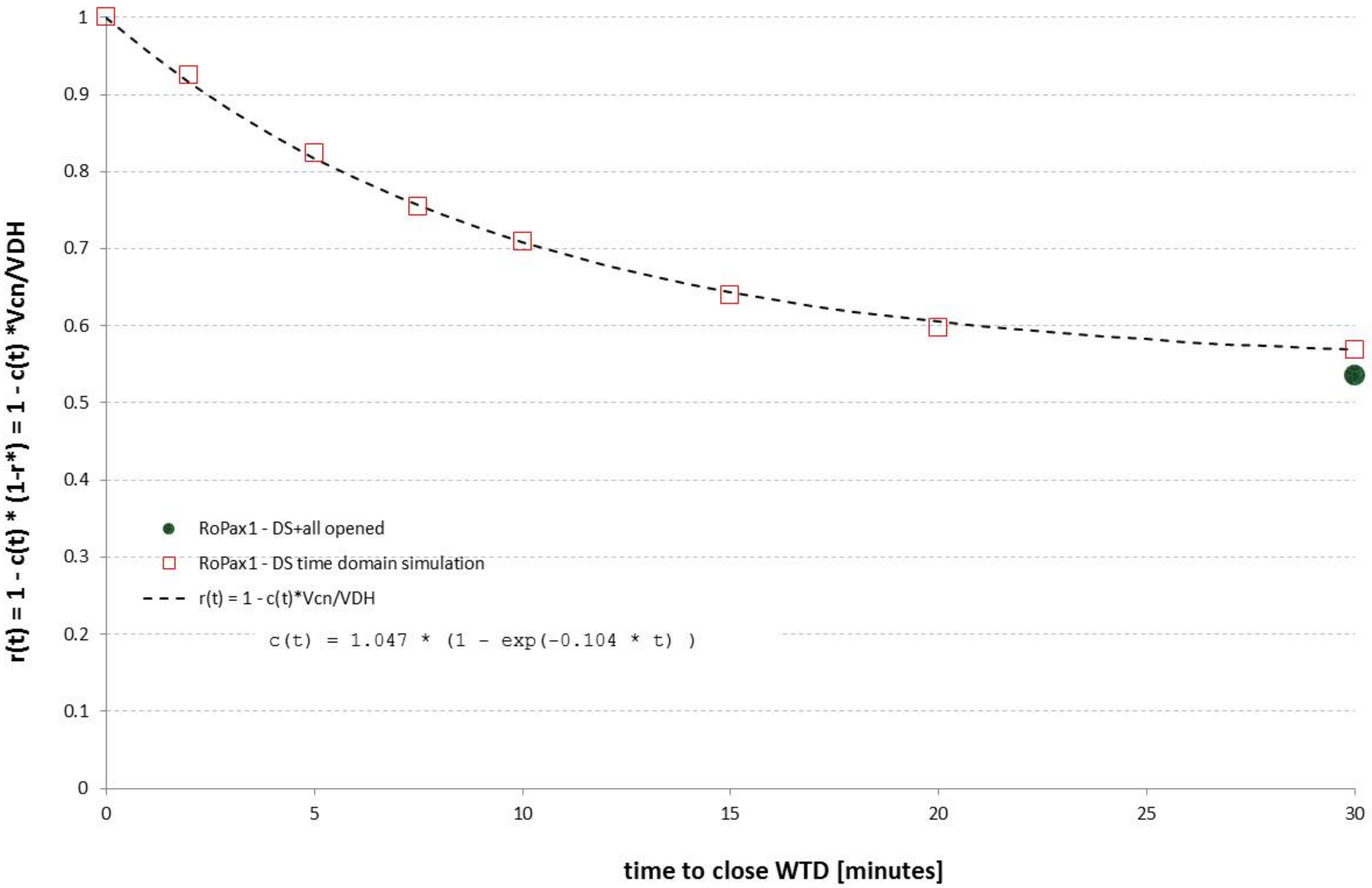

Figure 60 RoPax 1, ratio of index $A^{*}_{opened}/A^{*}_{closed}$ with WTD closed within given time t.

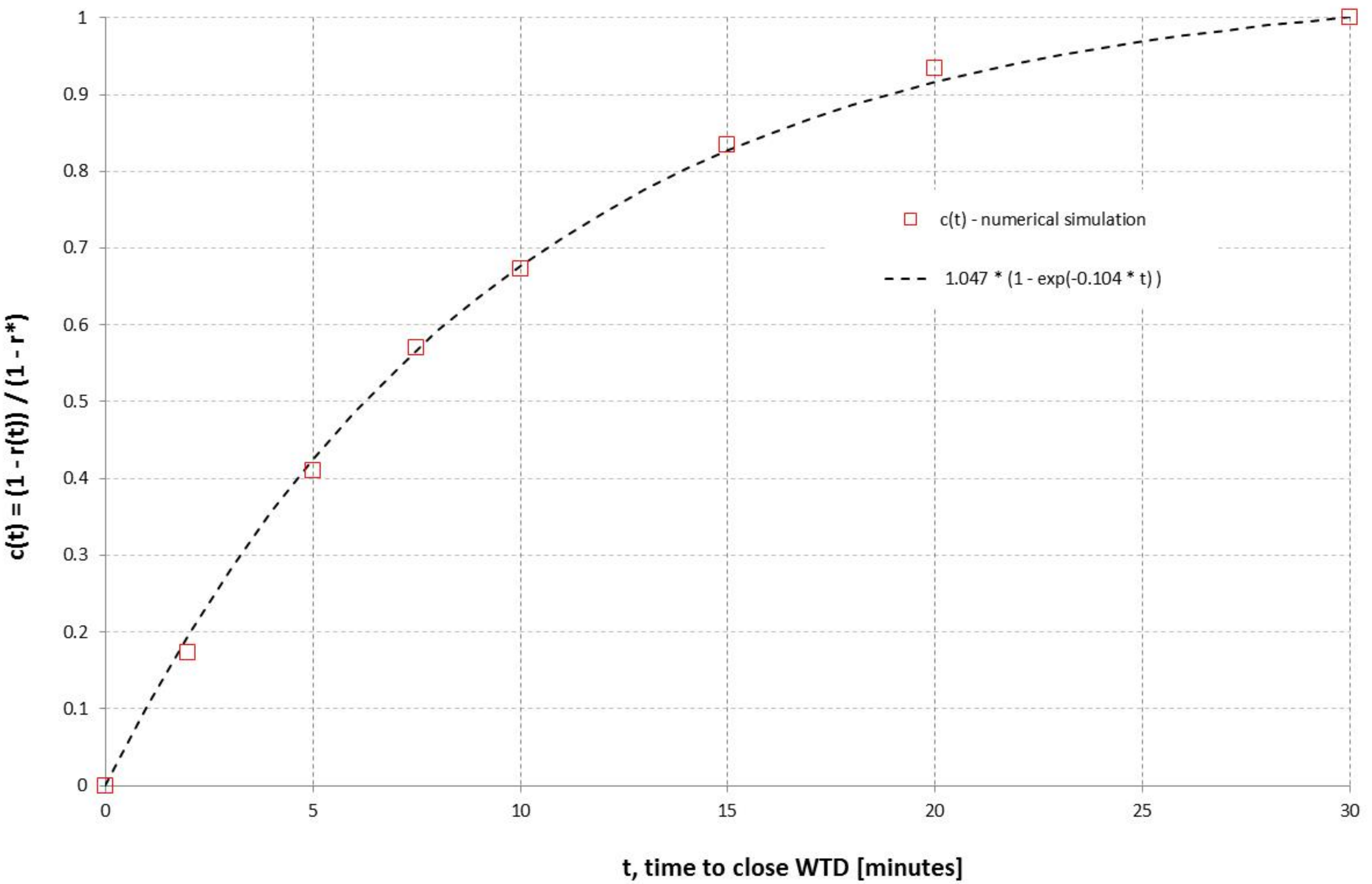

Figure 61 RoPax 1, factor of risk increase due to time lag in closure of doors.

Appendix 4 Reliability of water tight doors

WTD have a degree of inherent reliability, as every manufacturing process results in "imperfections" and deviations from intended properties of produced systems. Such reliability will be subject to not only manufacture process itself or materials used, but also to utility schedule and maintenance programme in a lifetime of a WTD. Appendix 5 presents with a sample maintenance schedule of WTD to demonstrate rigour required to properly maintain WTDs. Despite all endeavours by all concerned failures occur, as mentioned in **Appendix 1**, in various ways and due to various reasons. Door may malfunction as a result of inefficient maintenance, no maintenance, due to naturally expected faults, or due to accident itself. The malfunction may constitute inability of WTD to close, or loss of function of water-tightness due to faulty seals, lost hydraulic pressure to keep door in closed position, etc.

Reliability of single door

To represent potential contribution to risk of these reliability-related issues a technique is adopted to systematically incorporate any number of such sources of possible malfunctions, as presented in this chapter.

A reliability of a single component of a complex system (say of a WTD) may be modelled by a Weibull function, equation (12), assigning probability of a failure within some time t (in hours), $F(t|\eta,\beta)$, subject to some characteristics of that component, η,β.

$$F(t|\eta,\beta) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (12)$$

Characteristic of such components are reported to be very difficult to establish, and are often expected to be highly confidential data. An example of characteristics of components such as a door springs, valves and pressure tanks, has been sources as shown in Table 61.

Table 61 Reliability coefficients sourced from http://www.barringer1.com/wdbase.htm. The values below are shown as an example only.

$\eta_{spring} := 25000$	$\beta_{springs} := 3$
$\eta_{solenoid\_valve} := 75000$	$\beta_{solenoid\_valve} := 2$
$\eta_{pressure\_vessels} := 2000000$	$\beta_{pressure\_vessels} := 1.5$

Assuming as way of example that such a door spring, valve and pressure tank are the key critical components of a WTD, failure of either of which may compromise WTD function of providing watertight integrity, the probability of malfunction of the WTD in time of t hours may be assigned based on model (13).

$$P_{failure}(t) = 1 - \prod_i \left(1 - F(t|\eta_i, \beta_i)\right), \text{ where } t \text{ in hours} \quad (13)$$

The assigned probabilities of WTD failure, assuming the simple representation of mechanism by the three components with characteristics given in Table 61, are shown in Figure 62. The WTD would be expected to fail within one year with 6.3% probability. In other words, 1 in 16 such doors would be expected to fail annually.

The exact rates of failures of WTD should be derived for every specific door, preferably by their manufacturers, and for typical installation environment. Experimental data would probably be the most reliable datum for assessment proposed in this report, however theoretical model such as shown by means of equation (13), or more elaborate fault trees could be developed and disclosed at approval process. The latter offer possibility for systematic inclusion of as many components as judged to be representative of mechanisms of WTD operation, and thus may facilitate very detailed sensitivity analyses.

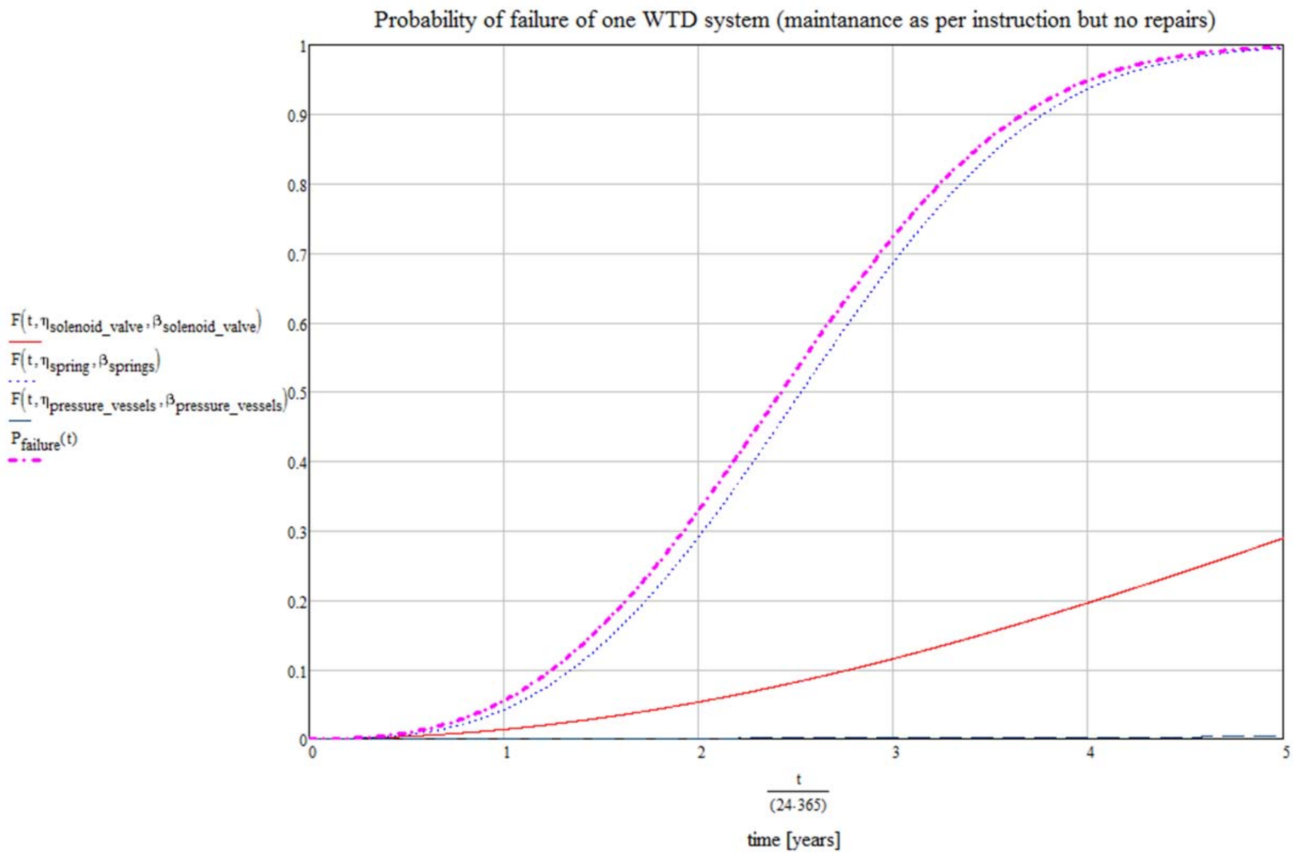

Figure 62 Probability of failure of single components and of the WTD system as a function of time.

Reliability of series of doors

Assuming that such data and/or models allow representing probability a door may fail during a flooding accident, it is now necessary to assign probability of failure of a series of WTD that are typically installed on a ship, and thus the degree of contribution to risk as a result. The task becomes rather complex due to existence of typically many WTD, each of which may fail.

Probability that a specific number of k WTD fail among total of n number of WTD, and provided probability of failure of each single WTD may be assigned as $p = P_{failure}(t)$, may be assigned according to binomial distribution given by equation (14) and shown in Figure 63.

$$P_k(k, n, p) = \frac{n!}{k! \cdot (n-k)!} \cdot p^k \cdot (1-p)^{n-k} \tag{14}$$

$n_d := 7$

$t := 1 \cdot 24 \cdot 365$ $\quad k := 0, 1 .. n_d$

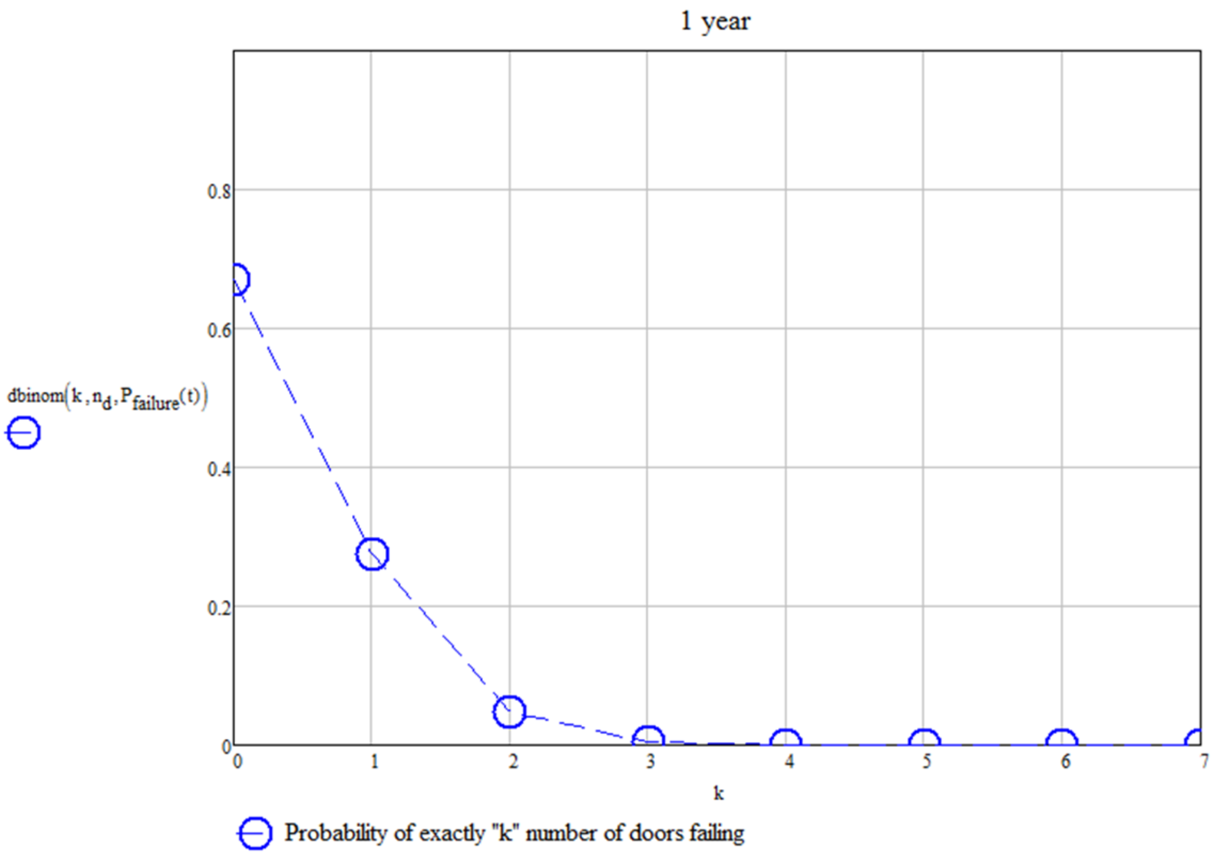

Figure 63 Probability of failure of exactly k number of doors among n doors.

Risk contribution

To now assign contribution of risk it would be necessary to consider each separate door, and each set of 2, 3, …, n of doors that might fail to close or retain water tightness. This is computationally challenging and would require constant monitoring of which doors exactly are opened at any one time, and thus what volume is exposed to further flooding.

It is proposed that instead an expected number of doors that fail is considered, which is given by $E_f(k) = P_{failure}(1year) \cdot n$, and for which a proportion of $1/n$ of the ratio V_{cn}/V_{DH} contributes to risk (assuming that crew actions will be ineffective). Furthermore, it is assumed that the remaining expected number of doors, $E_s(k) = (1 - P_{failure}(1year)) \cdot n$, would be successfully closed and remain watertight as intended. Such averaged impact of reliability may be applied to the factor $c(t)$ given by equation (11), since it allows to reflect crew inability to close such door by $c(t) = c(30min)$, as shown by equation (15).

$$c^*(t) = E_f(k) \cdot \frac{c(30min)}{n} + E_s(k) \cdot \frac{c(t)}{n} \quad (15)$$

After simple arithmetic operation, it appears that the impact of reliability may be represented by the following model (16), where it may be noted that $c(30min) = 1$.

$$c^*(t) = P_{failure}(1year) \cdot c(30min) + \left(1 - P_{failure}(1year)\right) \cdot c(t) \quad (16)$$

The model of impact of WTD may thus be proposed as given by equation (17).

$$r^*(t) = 1 - c^*(t) \cdot \frac{V_{cn}}{V_{DH}} \quad (17)$$

To demonstrate the application of the above model for risk quantification, the main assumptions of risk modelling is adopted. Namely, since risk modelling in Task 1 uses proportionality to 1-A for risk quantification, it is possible to quantify contribution to risk from WTD operation by considering the ratio (18).

$$dR = \frac{1 - r(t) \cdot A}{1 - A} \quad (18)$$

Example calculation of contribution of reliability of WTD to risk, on the basis of assumptions listed in Table 61, is presented in Figure 65. Assuming an annual failure rate of 1 per 16 doors, it would contribute some 3.3% of risk to life for a typical ship and a typical ship operation.

This contribution to risk diminishes with the amount of time it takes to close the doors. The longer is the delay the WTD are closed from the instant of flooding occurrence, the lesser is the risk contribution. If the WTD are closed at all times (or the time delay to close is 0 minutes), then the WTD contribution to risk derives only from reliability of such doors. This relationship is shown in Figure 66.

The time to close the WTD, in case they remain opened at the instance of a flooding incident, is matter of crew training and “safety culture”, perhaps varying from ship to ship. Therefore, it appears very difficult to commit to a specific quantity. A method to address this uncertainty is presented next.

Uncertainty

Based on publically available information, it appears that the command and closure of WTD may take some 5 minutes, e.g. [17]. Cases such MV ESTONIA, indicate that it may take as long as 12 minutes to close WTD, e.g. [19]. According to discussions with ship operators, there seems to be consensus that 5 minutes to close WTD may be representative of today’s manner of operation.

To represent this perceived degree of uncertainty it is proposed to consider model such as given by (19) and shown in Figure 64, with $\mu = 1.609$ and $\sigma = 0.405$. It assumes a spread in feasibility of doors closure within time of between one minute to some twenty minutes, with median time of five minutes.

$$f_T(t) = \frac{1}{\sigma \cdot t \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{1}{2 \cdot \sigma^2} \cdot (ln(t) - \mu)^2} \quad \text{time in minutes} \qquad (19)$$

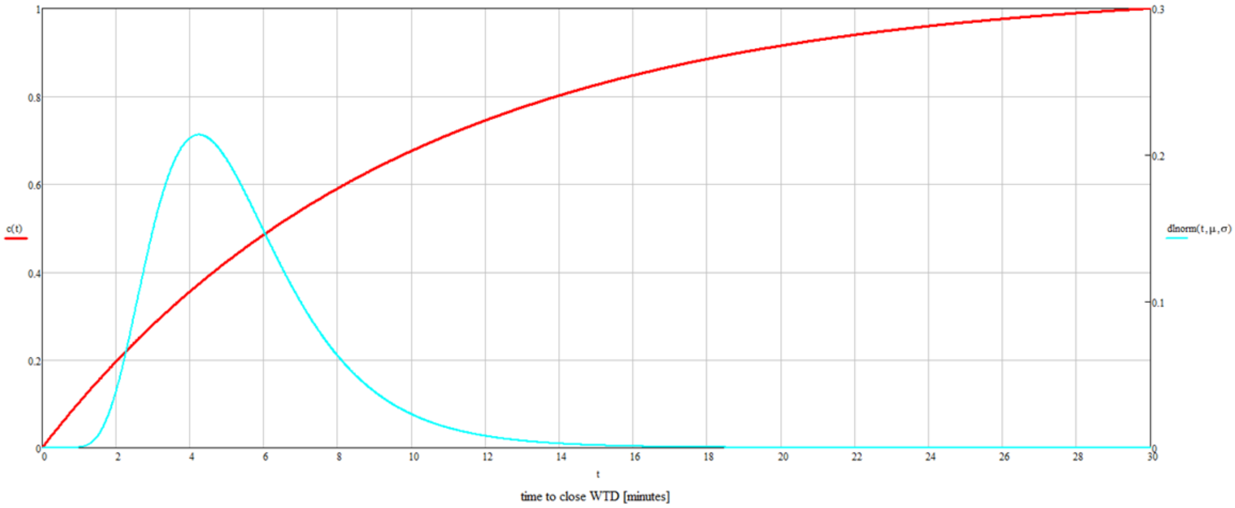

Figure 64 Assumed distribution of probability density for a plausible time to close WTD after incident for calculation of expected value of the reduction factor E(c*(t)).

The remaining task is to extend model (17) for the above assumed information. It is proposed that an expected value of this contribution be considered as the final construct representing the impact of WTD. The expected value of the factor c(t), may be calculated as given by equation (20).

$$C^* = E\left(c^*(t)\right) = \int_t d\tau \cdot f_T(\tau) \cdot c^*(t) = 0.471 \qquad (20)$$

The final form of the model of impact of WTD would thus take the form (21).

$$r^* = 1 - C^* \cdot \frac{V_{cn}}{V_{DH}} \quad \text{where } C^* = 0.471 \qquad (21)$$

If time to close is to be considered then model (17) would be appropriate.

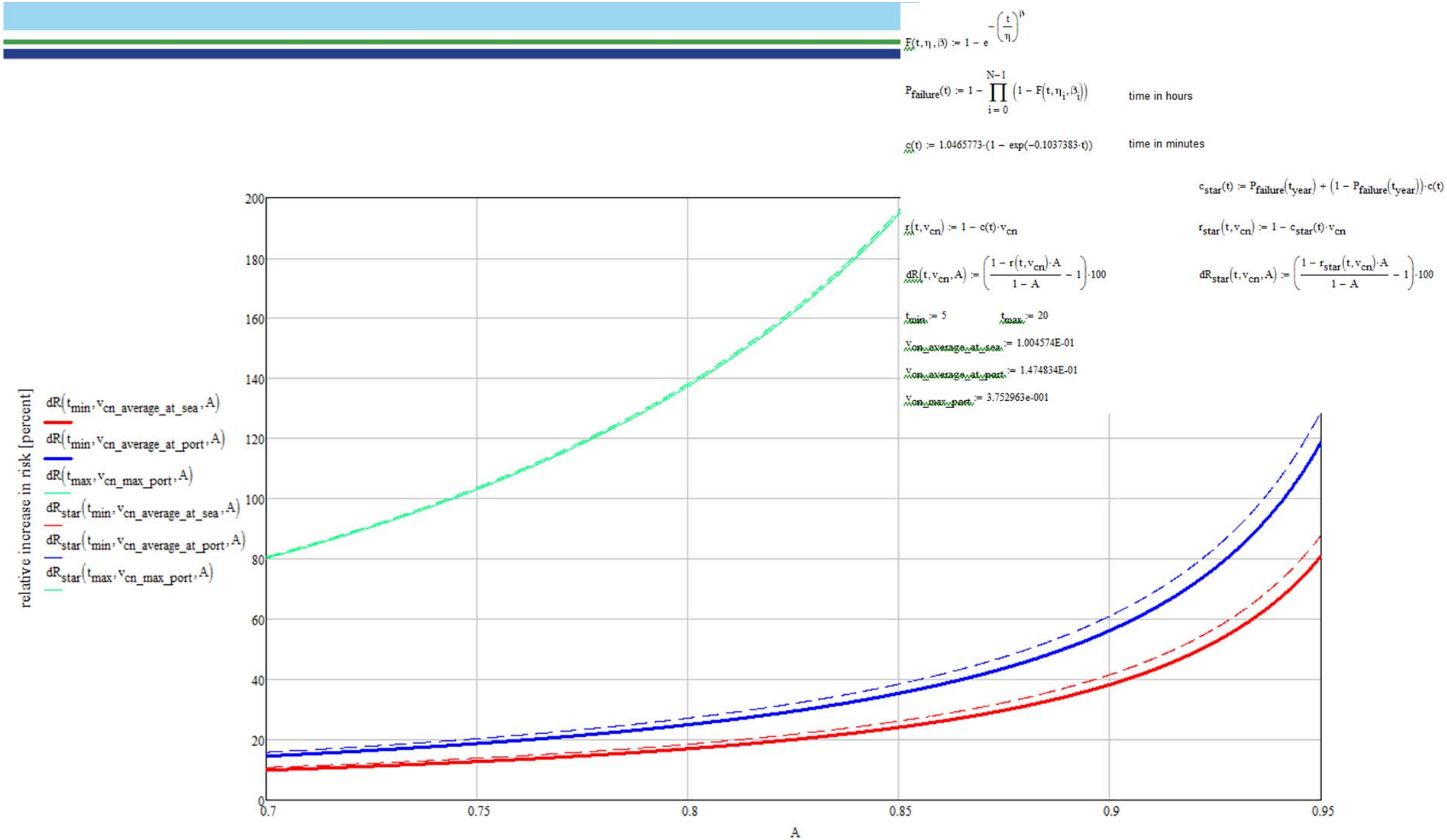

Figure 65 Example of a test of sensitivity of the impact of WTD on risk contribution due to reliability.

Please note in the above figure the decreasing contribution to risk for longer times to close doors (green line), shown also in Figure 66.

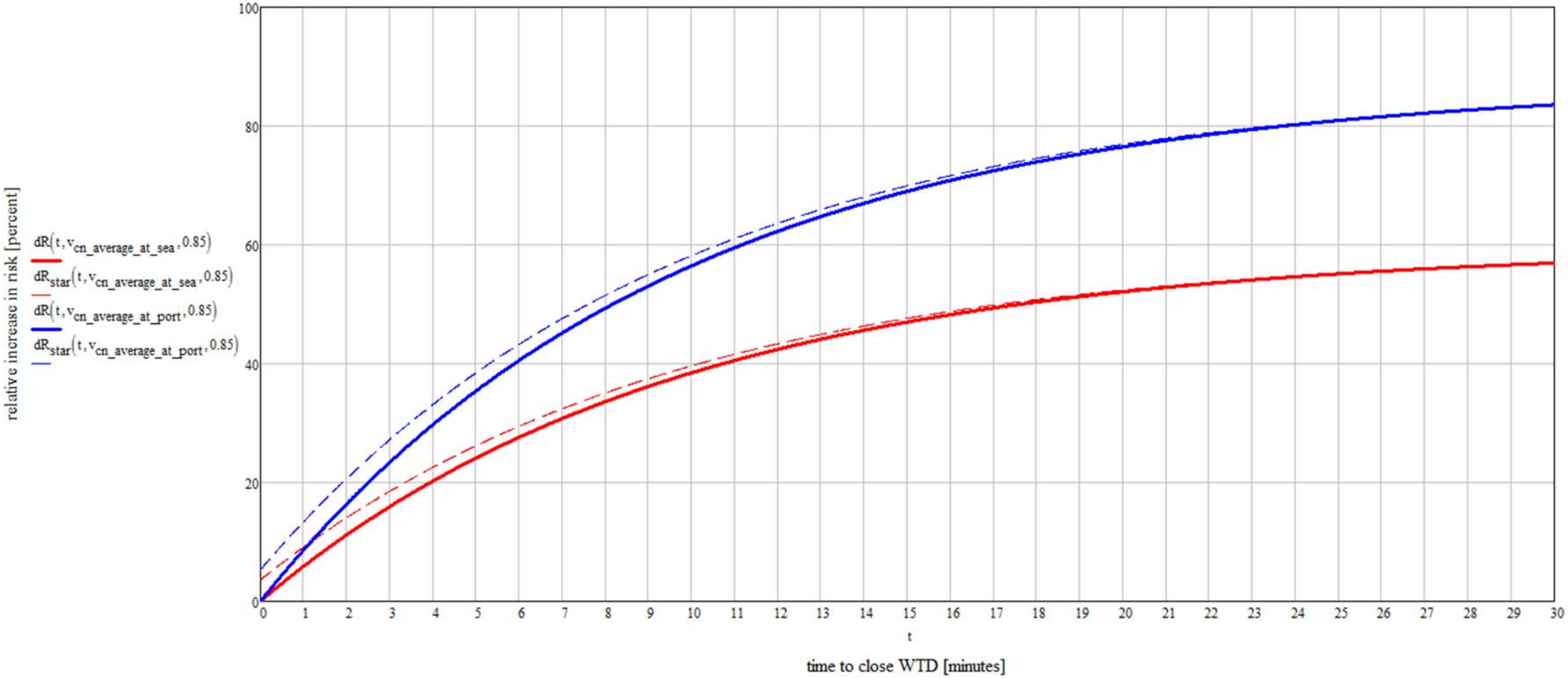

Figure 66 Sensitivity of the risk contribution to time of closure of WTD after incident of water ingress (solid lines) and impact of reliability (dashed lines).

Appendix 5 Maintenance schedule of WTD

MAINTENANCE INSTRUCTIONS

FOR

WATERTIGHT DOORS

WATERTIGHT SLIDING DOORS CLASS III

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SAFETY WARNINGS

THE WATERTIGHT DOOR CLOSES WITH HIGH FORCE. ANY OBJECT IN THE PASSWAY OF THE DOOR WILL BE CRUSHED. DO NOT WALK THROUGH A MOVING DOOR OR A DOOR WHICH IS NOT COMPLETELY OPEN.

THE SYSTEM HAS HIGH HYDRAULIC PRESSURE

BEFORE SERVICING THE DOORS OR SHUT DOWN OF ELECTRICAL POWER FOR CONTROL AND INDICATION:

BLEED THE ACCUMULATOR. SEE PARAGRAPH 2, SHUTDOWN PROCEDURE.

EMERGENCY CLOSING FROM THE CONTROL STATION:

ALL OPEN DOORS WILL AUTOMATICALLY CLOSE.

ELECTRICAL POWER FAILURE:

IF POWER TO BOTH ALARM AND CONTROL SYSTEMS FAIL AT THE SAME TIME, THE DOOR(S) WILL AUTOMATICALLY CLOSE WITHOUT WARNING SIGNAL.

NOTE: PLEASE BE ADVISED OF THE DANGERS OF OPERATING SLIDING WATERTIGHT DOOR SYSTEMS, IT IS EXTREMELY IMPORTANT THAT ALL CREW MEMBERS ARE AWARE OF HOW THE SLIDING WATERTIGHT DOOR SYSTEM OPERATES.

THE CREW SHOULD BE TRAINED TO OPERATE THE DOORS UNDER ALL CIRCUMSTANCES, INCLUDING: 1. "LOCAL CONTROL" MODE; 2. WHEN SWITCHED TO AND WHEN IN "DOOR CLOSE" MODE; AND 3. MANUALLY.

SEE FUNCTIONAL DESCRIPTION.

IMS RECOMMENDS THAT EACH PERSON USING THE DOORS SHOULD DEMONSTRATE TO THE SAFETY TRAINOR THAT THEY ARE CAPABLE OF PROPERLY OPERATING THE DOOR.

Table of contents

1. INTENTIONS AND LIMITATIONS

This maintenance instruction is based on the operation frequency of the doors. To get a correct maintenance frequency, an estimate of the operation frequency has to be made for each door. This instruction is based on the operation frequency of 100 operations per 24 hour day. If the doors are used with a higher frequency, the maintenance frequency needs to be changed accordingly.

This instruction covers the preventive maintenance of the door, while the testing of the door is to be according to "System Functional Test Procedure".

It is essential to maintain the recommended maintenance frequency to ensure the proper and correct function of the door at all times. This instruction is limited to use as a guide only. It is up to each vessel's crew to determine how this maintenance instruction shall be implemented and followed.

2. SHUTDOWN PROCEDURE

Warning: Follow this shutdown procedure before servicing the door!
Follow the same procedure if the doors are going to be shut down for a period of time.

1. Do not shut down the power for control and indication before the following steps are completed locally at the doors.

2. Locally at the door:
   - We advise that the door is marked with "Service" or similar note.
   - Remove the operating handles. Take off the cover and put the handles back on.
   - Switch off the power to the electric pump-motor (button marked F1, located in the motor starter coil).
   - Drain the hydraulic accumulator by operating the door back and forth with the operation handle until the door stops and the oil pressure is 0 Bar.
   - Use the manual pump to put the door in the wanted position.

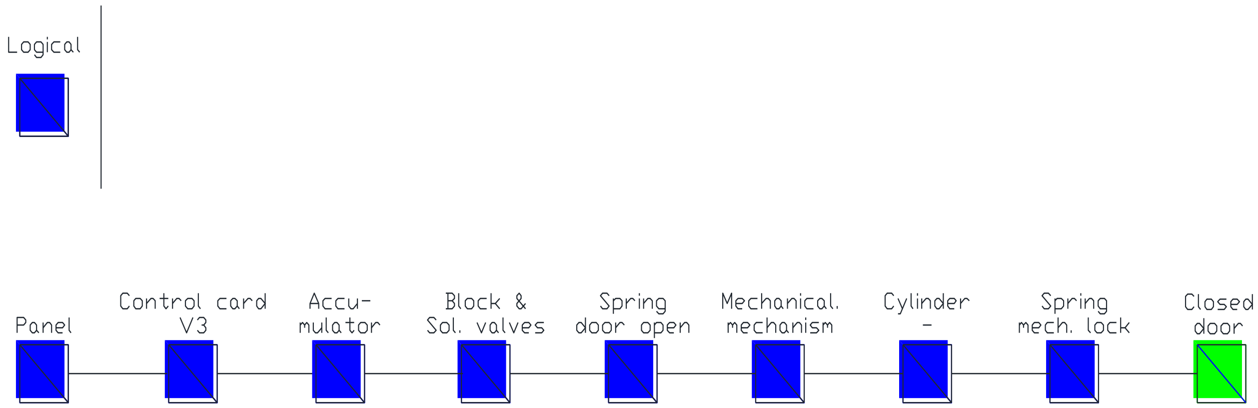
   Repeat item 2 for all doors that will be serviced or shut off.

Be aware that there is still pressurized nitrogen in the gas side of the accumulator.

3. MANDATORY MAINTENANCE FOR WATERTIGHT SLIDING DOORS

The **mandatory operation** is the remote closing function. Starting from the bridge control panel and ending by a door-closed-signal when the door is in safe position (closed). Further the **mandatory task** is water tightness.
Parts not mandatory for the ship stability as local alarms, speed control etc are or could be mandatory related to **personal security**. It is thereof in our opinion a mistake to disregard the importance of any door item.

Mandatory spare parts for the remote closing function are:



Mandatory spare parts for personal safety are:

- Failure on the limit switch, S1 Local control – The door may close.
- Failure on solenoid valve, Y1 (only hydraulic doors) local control. – The door may close.
- Failure of spring for door close, local control - The door may close.
- Failure of door open spring. - The door may open. (Not if lock down)
- Safety strip failure (if mounted) in Local control mode. – Door may not function as intended.
- Safety strip failure (if mounted) in Door closed mode. - Door may not function as intended.
- Warning light for door closed mode

4. RUBBER GASKET REPAIR

IMS strongly recommends that service and repair of the door rubber sealing is to be done by an IMS approved service engineer/service technician, to ensure the watertight integrity of the door.

Our service engineers are highly trained in the quality repair and replacement of the rubber sealing.

5. MAINTENANCE FOR EVERY 3000 OPERATIONS OR EVERY MONTH.

To be checked:	Comments	References
Make sure the door sill is free of dirt and loose particles, also behind the door. Clean door sill if necessary.		-----
Make sure the door frame is free of dirt and loose particles. Clean door frame if necessary.		-----
Make sure the gasket is free of dirt and loose particles. Check the gasket for damages. Clean gasket if necessary.		-----
Lubricate the gasket with silicone oil.		-----
Check hydraulic system for leakage. Take special consideration to the following points: - Hydraulic cylinders - Pipes - Pipe connections - Hydraulic hand pump		Hydraulic diagram
Check the cams on the operation shaft and retighten the set screws.		Sketch 2 and 3
Check the switch for door operation and retighten the bolts that hold the switch.	Tightening torque 60Nm	Sketch 2 and 3
Nitrogen pressure in accumulator, and refill if necessary. See section 11.		Maintenance Instructions
Lubrication of mechanical parts. See section 10.		Maintenance Instructions
If safety strip:Clean the laser reflector mirror		
If safety strip: Visual exam the laser sensor and the associated cabling		

6. MAINTENANCE FOR EVERY 20000 OPERATIONS OR EVERY 6 MONTHS.

To be checked:	Comments	References
Check oil level and refill if necessary		Lubricant and Oil chart
Clean the gasket with White Spirit.		-----
Lubricate the gasket with silicone oil.		-----
Check wheels and bearing for excessive wear. Replace bearings if necessary.	Wheel size is stamped on side of wheel	Maintenance Instruction
Test of battery capacity for control and alarm/ indication system.		Shutdown procedure and "UPS power supply"

7. MAINTENANCE FOR EVERY 40,000 OPERATIONS OR EVERY YEAR.

To be checked:	Comments	References
Replace springs for operation mechanism.	Door open and close springs must be replaced simultaniusly	See Sketches 2 and 3.
Replace wheels and bearings.	Wheel size is stamped on side of wheel	Maintenance Instructions
Check rails for excessive wear. Replace if necessary.		Maintenance Instructions

8. MAINTENANCE FOR EVERY 80,000 OPERATIONS OR EVERY 24 MONTHS.

To be checked:	Comments	References
Replace oil	See Lubricant and Oil chart for correct cleanness of oil	Lubricant and Oil chart

9. MAINTENANCE FOR EVERY 36 MONTHS.

To be checked:	Comments	References
Replace batteries for control and alarm/ indication system.		Shutdown Procedure and "UPS power supply"

10. MAINTENANCE FOR EVERY 160,000 OPERATIONS OR EVERY 48 MONTHS.

To be checked:	Comments	References
Replace oil filter.		Lubricant and Oil chart

NOTE 1!
Whenever the hydraulic pump is replaced, the hydraulic oil and filter must be replaced at the same time.

NOTE 2!
The first oil change after the start-up of the doors shall include oil filter change.

NOTE 3! When painting the door or near the door, be sure to protect the rubber gasket, the piston rods on the cylinder(s) and other vulnerable parts.

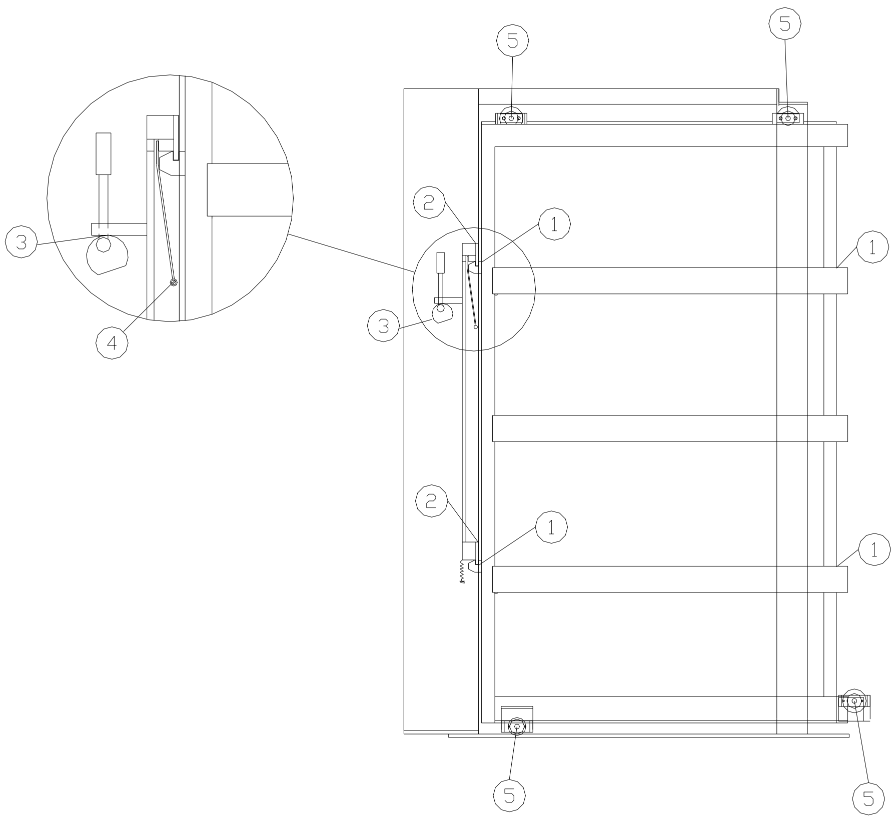
11. MAINTENACE FOR EVERY 60 MONTHS (5 YEAR)

To be checked	Comments	References
If safety strip: Replace laser sensor		
A 5 year service on the watertight sliding doors has to be performed by IMS approved service engineers. A certificate will be issued by IMS and the doors are approved according to SOLAS Chapter II.		

12. LUBRICATION OF MECHANICAL PARTS

Sketch 1 shows the locking device assembly on the door with parts to be lubricated.

Sketch 1



Pos.	Item	Lubrication
1	Cleat bolts	Synthetic grease
2	Locking device, flat bar	Synthetic grease
3	Lifting cam and arm	Synthetic grease
4	Bolt for locking arm.	Penetrating oil (CRC 5-56, WD-40)
5	Wheel. If no grease nipple on the wheels, the self lubricator bearing have no need for lubrication. If grease nipple installed use synthetic grease.	If lubrication use synthetic grease.

Note: Number of cleat bolts may vary.

13. HYDRAULIC ACCUMULATOR

The hydraulic accumulator is located in the doorframe. *See hydraulic diagram* for correct pre-charged nitrogen pressure.

Check pre-charged nitrogen pressure at start up and **every month** as follows:

1. Locally at the door:

   - Remove the operating handles. Take off the cover and put the operating handles back on.
   - Switch off the power to the electric pump-motor (button marked F1, located in the motor starter coil).
   - Drain the hydraulic accumulator by operating the door back and forth with the operation handle until the door stops and the oil pressure is 0 bar.
   - Use the manual pump to put the door in the wanted position.

2. While looking at the manometer, start the pump again! When the pump starts, the pressure gauge increases fast from "0" up to the actual pre-charged nitrogen pressure. If the pressure is within the limits, refit the cover plate, if not, continue with refilling of gas.

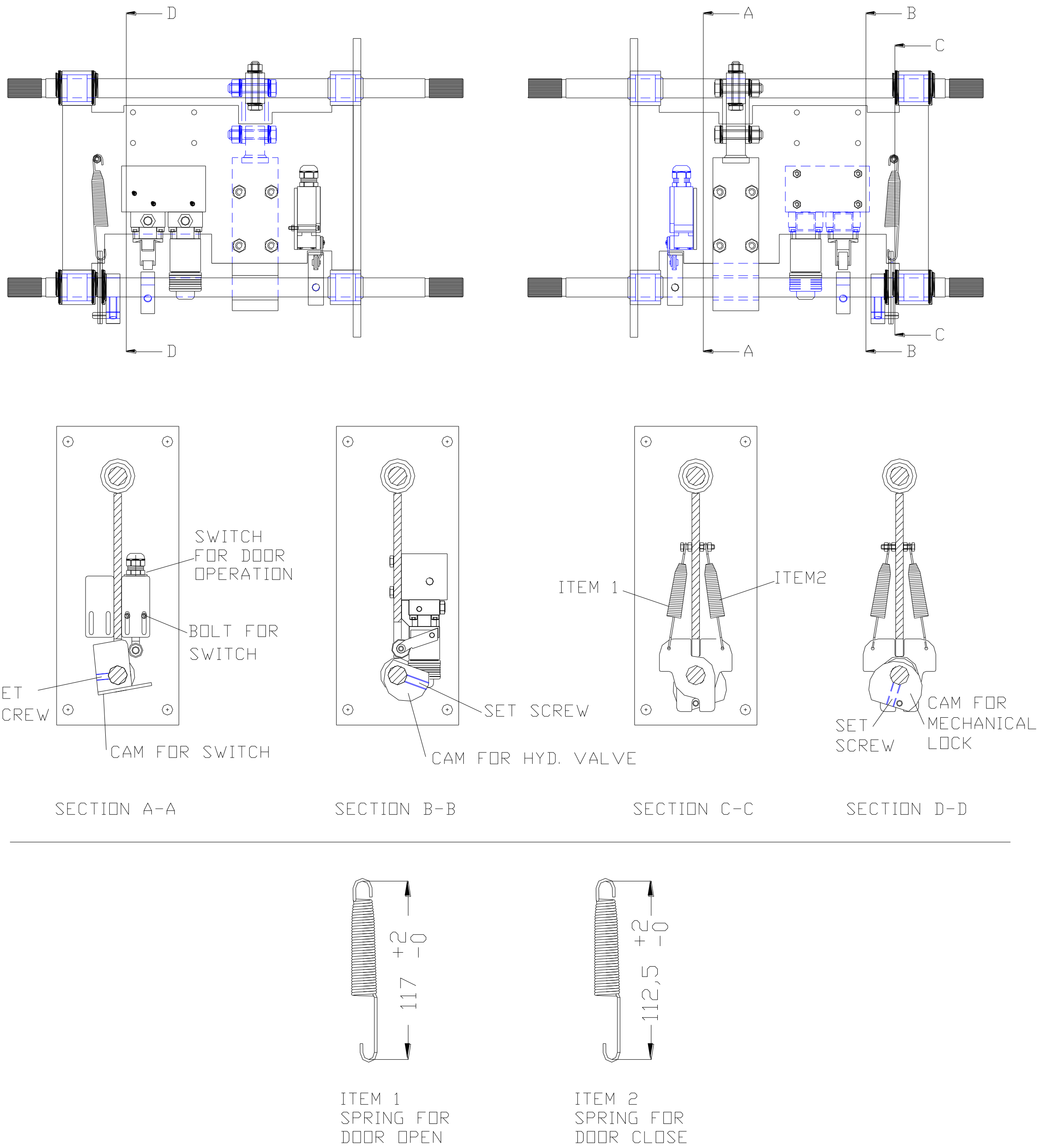
3. Refilling nitrogen: When the hydraulic pressure is drained and the manometer shows 0 bar, disconnect the rupture plug on the top of the accumulator. Connect the charging gear. Charge the accumulator. Repeat item 2 to check new pressure.

4. Check that the pressure reaches the normal level (working pressure is given in the hydraulic diagram).

5. Refit the cover plate and operating handles.

14. OPERATION MECHANISM, LEFT SLIDING DOOR

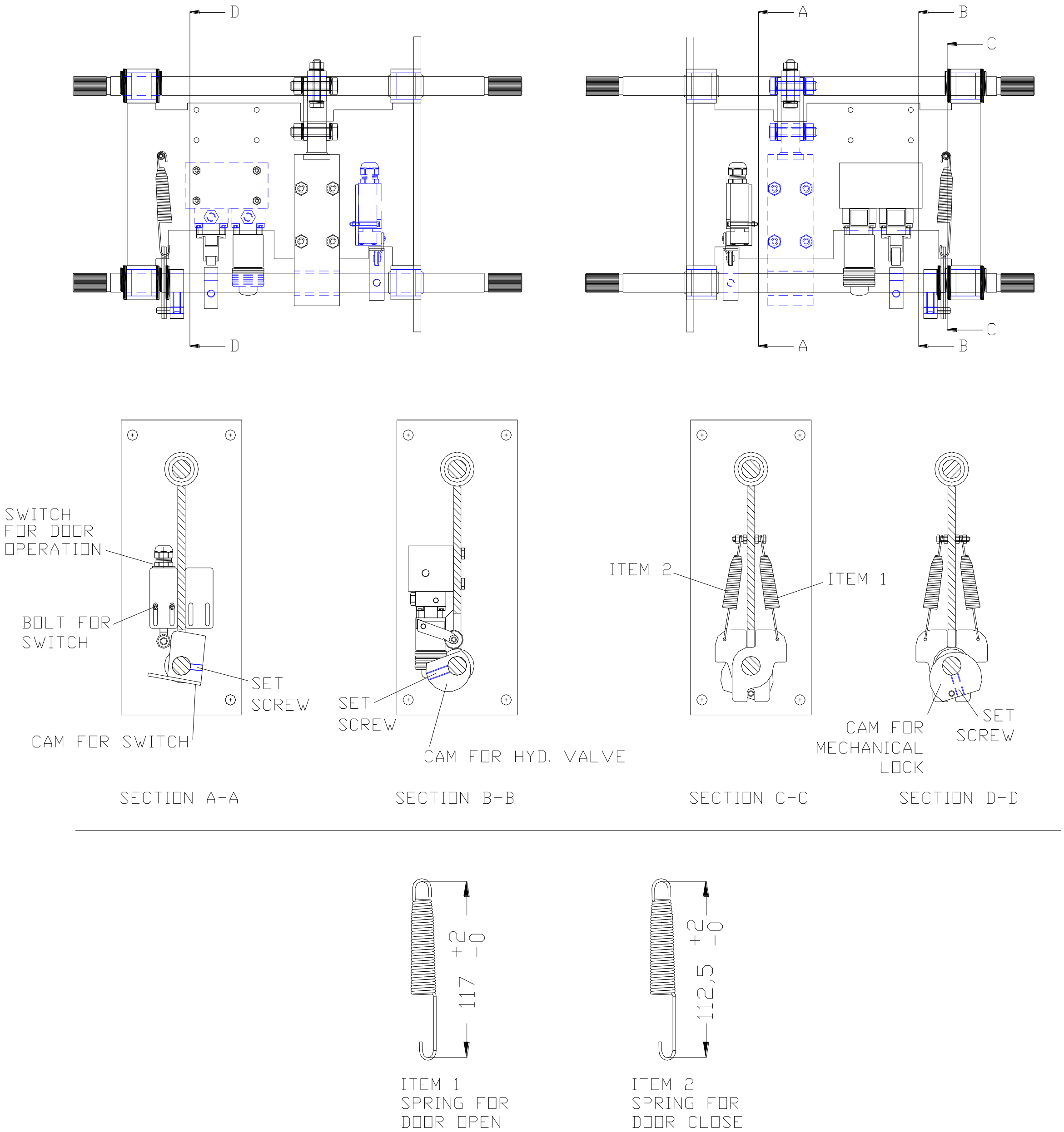
Sketch 2



The maintenance frequency in this instruction is based on the use of correct springs for the operation mechanism indicated on this page.

15. OPERATION MECHANISM, RIGHT SLIDING DOOR

Sketch 3



The maintenance frequency in this instruction is based on the use of correct springs for operation mechanism indicated on this page.

16. RAILS AND WHEELS

To prevent excessive wear of the rubber gasket, the hydraulic cylinder, and the cleat bolts, it is essential to keep the wheels and rails in good condition.

Worn rails can be compensated by replacing the wheels with larger inner diameter. If the rails are worn uneven more than 2mm, the rails need to be replaced. See sketch 4.

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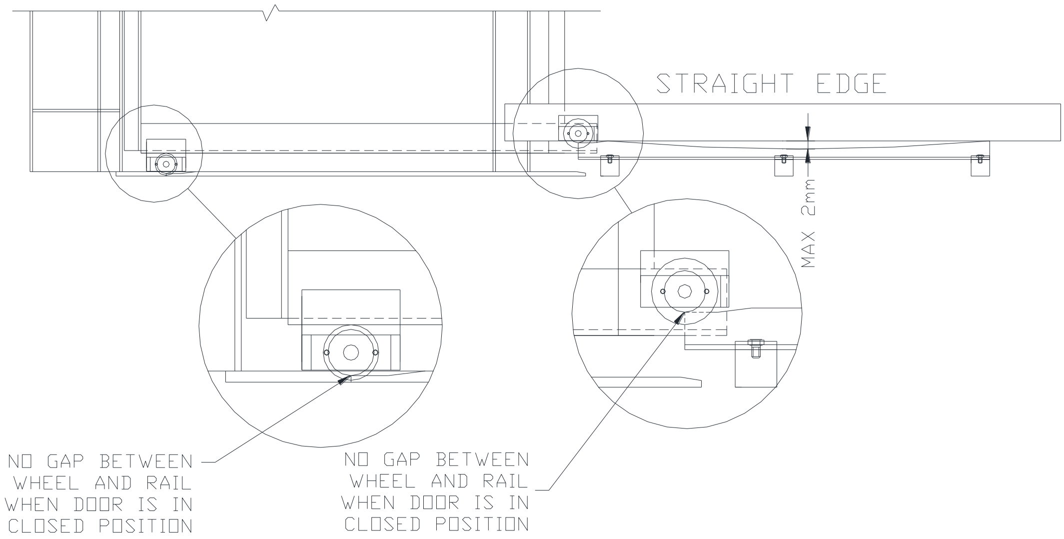
16.1. VALID FOR F12, MR, AND AH DOORS

16.1.1. BOTTOM RAILS AND WHEELS

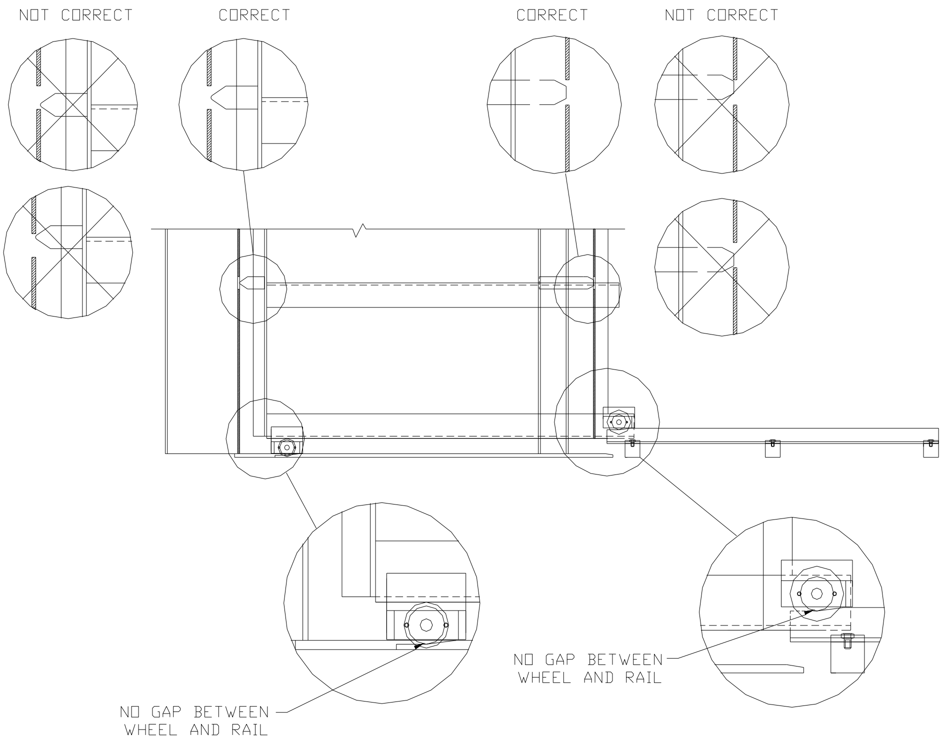
Sketch 4, BOTTOM RAIL

There is to be no clearance/gap between wheel and rail in closed position



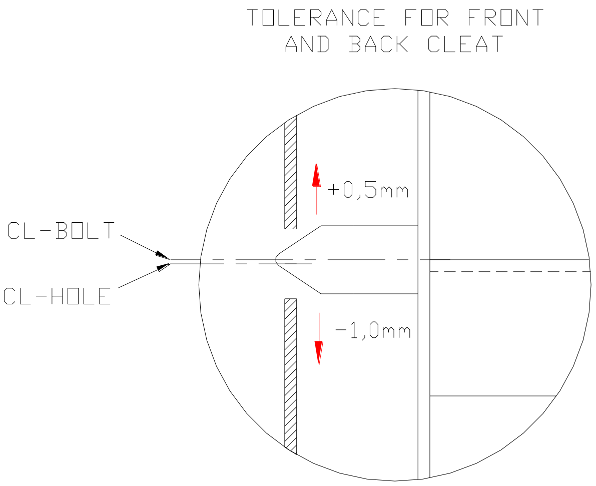
Sketch 5, BOTTOM WHEEL

When operating the door, it shall not drop or lift when the door is entering or leaving the cleat bolts.
It is the function of the wheels and the rails to lift the door when the door is leaving the closed position.



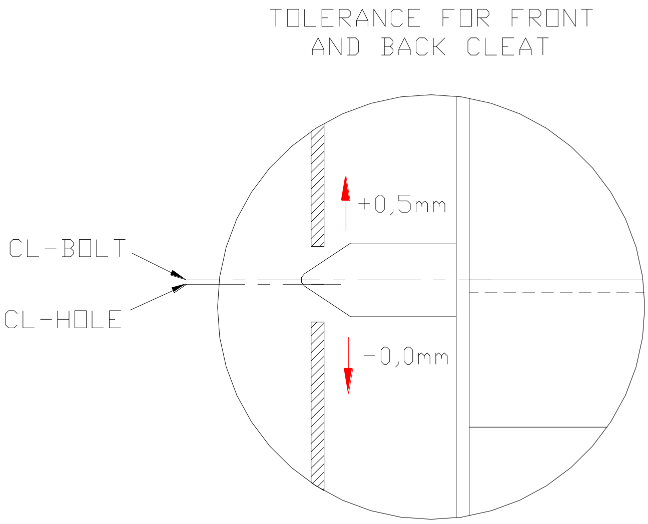
16.1.2. Tolerances for wheel wear

Check the height of the cleat compared to the bolt hole, if tolerances in sketch 6 are exceeded, wheels must be replaced:



Sketch 6 Cleat height tolerances before replacement

After replacing wheels the height of the cleat compared to the hole, shall be within tolerances in sketch 7:



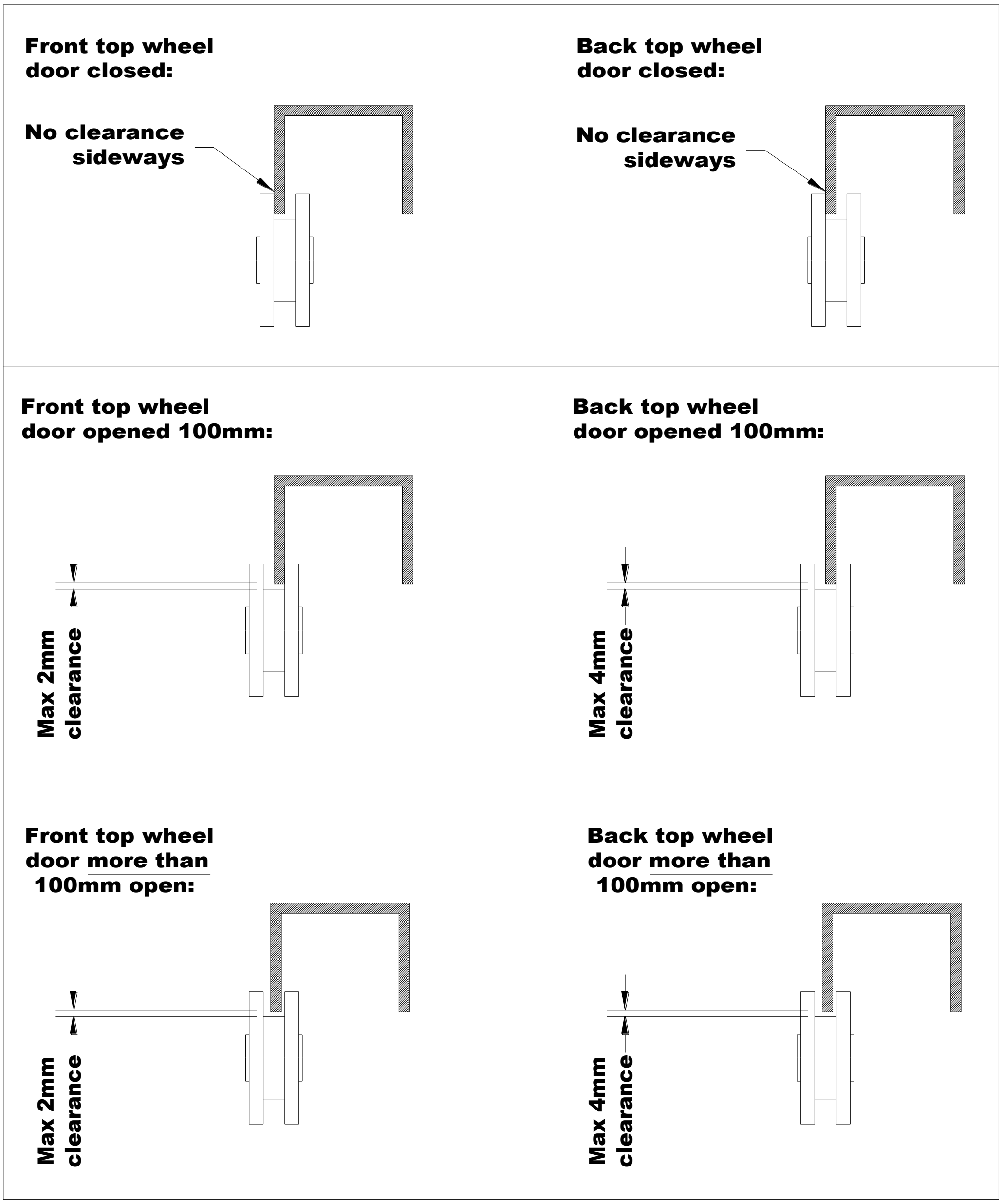
Sketch 7 Cleat height tolerances after replacement

TOP RAILS AND WHEELS FOR F12, MR, AND AH DOORS

Warning!! Only remove one top wheel at a time. If both top wheels are removed the door blade may fall causing property damage and/or personal injury or death.

Sketch 8, TOP WHEEL, shown example is a right sliding door (opening towards right) and is seen from behind the particular wheel.

Demands for clearance between top wheels and rail



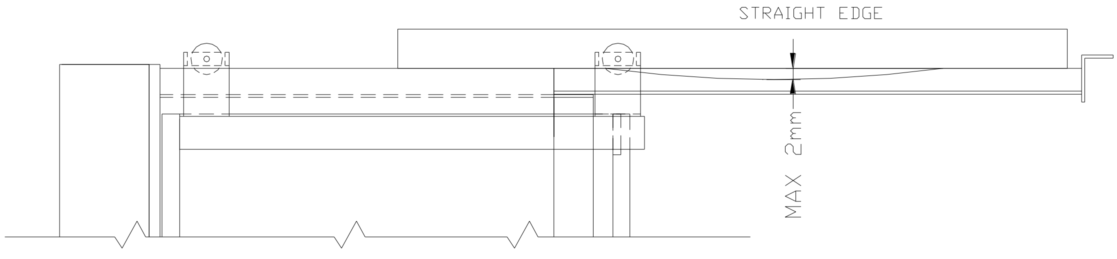
16.2. VALID FOR N200/280 DOORS

16.2.1. TOP RAILS AND WHEELS

Warning!! Only remove one top wheel at a time. If both top wheels are removed the door blade may fall causing property damage and/or personal injury or death.

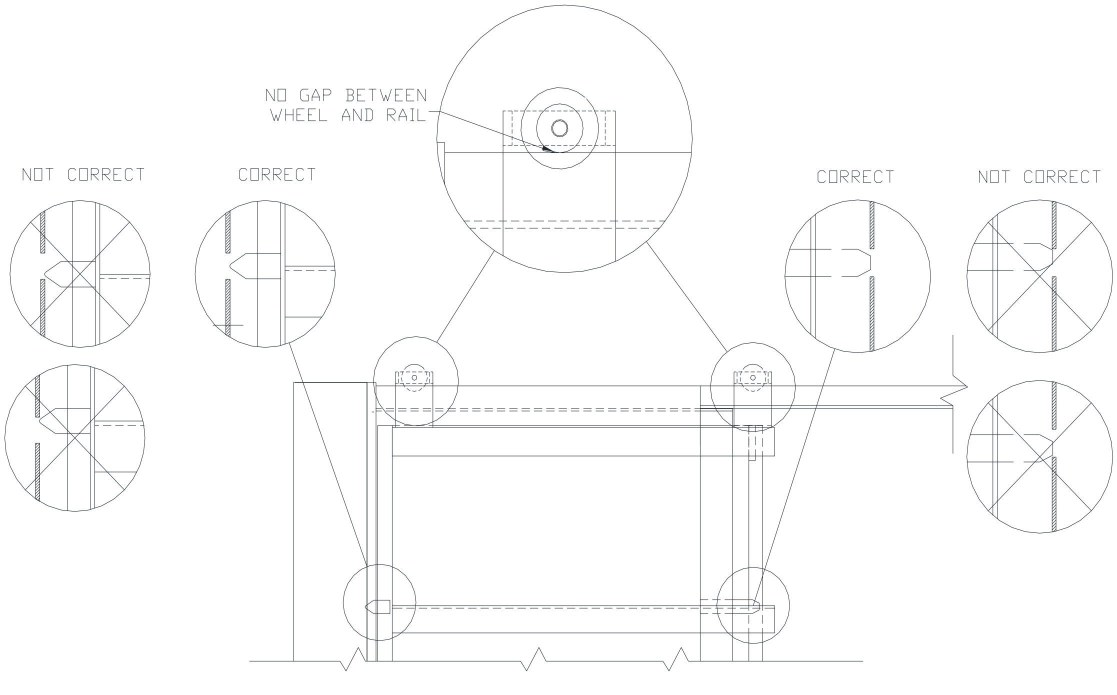
Sketch 9, TOP RAIL

There is to be no clearance/gap between wheel and rail in closed position



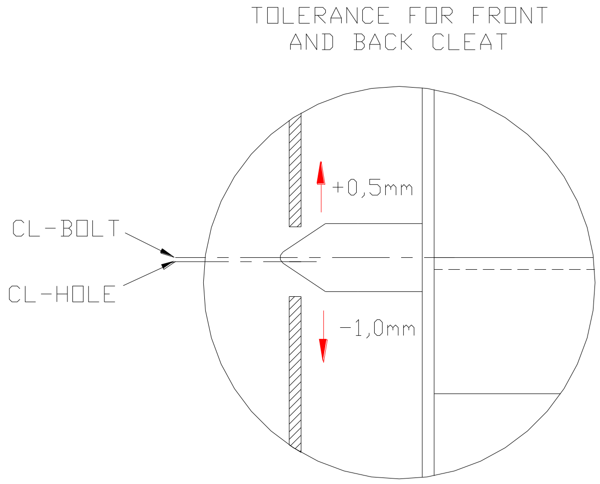
Sketch 10, TOP WHEEL

When operating the door, it shall not drop or lift when the door is entering or leaving the cleat bolts.



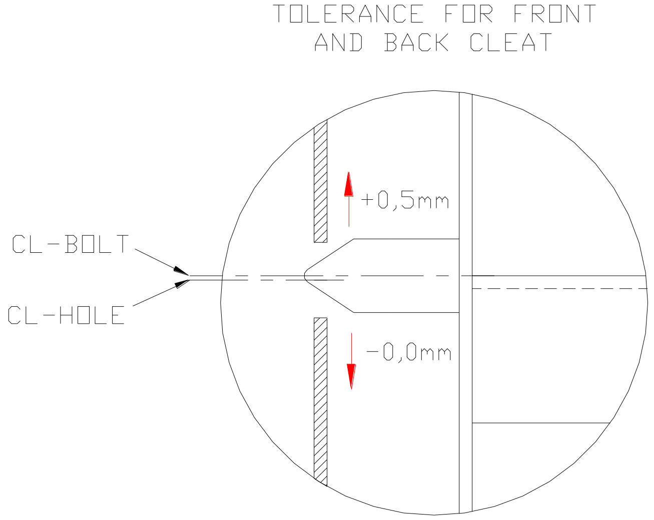
16.2.2. Tolerances for wheel wear

Check the height of the cleat compared to the bolt hole, if tolerances in sketch 11 are exceeded, wheels must be replaced:



Sketch 11 Cleat height tolerances before replacement

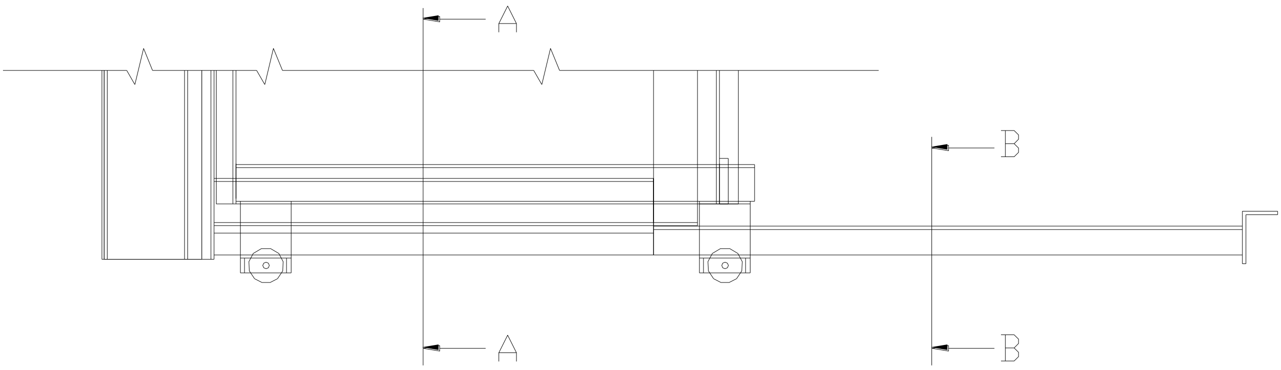
After replacing wheels the height of the cleat compared to the bolt hole, shall be within tolerances in sketch 12:



Sketch 12 Cleat height tolerances after replacement

16.2.3. BOTTOM RAILS AND WHEELS FOR N200/280 DOORS

Sketch 13Bottom rail



See Sketch 14

Sketch 14, BOTTOM WHEEL, shown example is a right sliding door (opening towards right) and is seen from behind the particular wheel.

Demands clearance between bottom wheel and rail