NATIONAL TECHNICAL UNIVERSITY OF ATHENS

SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

DIVISION OF SHIP DESIGN AND MARITIME TRANSPORT

TITLE

Development of vessel collision avoidance model with emphasis on the Role of Human Factor

Diploma Thesis

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Abbreviations

Used Abbreviation	Full Form
AGCS	Allianz Global Corporate and Specialty
BN	Bayesian Network
COLREGs	International Regulations for Preventing Collisions at Sea
CN	Collision
CPN	Coloured Petri Net
D-S	Dempster-Shafer
DCPA	Distance at Closest Point of Approach
DPN	Deterministic Petri Net
ECDIS	Electronic Chart Display and Information Systems
E/R	Engine Room
ET	Event Tree
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
GSPN	Generalised Stochastic Petri Net
IMCO	Inter-Governmental Maritime Consultative Organisation
IMDG Code	International Maritime Dangerous Goods Code
IMO	International Maritime Organisation
MARPOL 73/78	International Convention for the Prevention of Pollution from Ships
MDTC	Minimum Distance to Collision
NM	Nautical Mile(s)
NOx	Nitrogen Oxides
NTSB	National Transportation Safety Board
OOW	Officer of the Watch
PIPE	Platform Independent Petri net Editor
PN	Petri Net
SECAs	Sox Emission Control Areas
SMS	Safety Management System
SOLAS	Safety of Life at Sea
SPN	Stochastic Petri Net
SOx	Sulphur Oxides
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
TCPA	Time at Closest Point of Approach
TPN	Timed Petri Net
TSBC	Transportation Safety Board of Canada

UNCTAD	United Nations Conference on Trade and Development
ULCC	Ultra Large Crude Carrier
VLCC	Very Large Crude Carrier
VOCs	Votatile Organic Compounds

Περίληψη

Η παρούσα διπλωματική εργασία αποτελείται από 8 κεφάλαια κι έχει συγγραφεί με σκοπό τον υπολογισμό της πιθανότητας σύγκρουσης πλοίων. Προκειμένου να πραγματοποιηθεί ο εν λόγω υπολογισμός, το ενδεχόμενο ατύχημα σύγκρουσης μεταξύ δύο πλοίων μελετήθηκε υπό ανθρωποκεντρικό πρίσμα, δηλαδή εξετάσθηκε ο ρόλος του ανθρώπινου παράγοντα στην συντέλεση του θαλάσσιου ατυχήματος. Έτσι, χτίσθηκε ένα ποιοτικό μοντέλο εξέλιξης της πορείας σύγκρουσης μεταξύ των πλοίων, αξιοποιώντας την πλατφόρμα Platform Independent Petri Net Editor (PIPE), η οποία, όπως δηλώνει και η ονομασία της, αποτελεί χρήσιμο εργαλείο σχεδίασης και μελέτης των δικτύων Petri. Βάσει του αναφερθέντος ποιοτικού μοντέλου, ποσοτικοποιήθηκαν οι αναμεμειγμένες μεταβλητές και τελικά υπολογίσθηκε η ζητούμενη πιθανότητα.

Όπως αναφέρεται και παραπάνω, η ανάλυση του ενδεχόμενου ατυχήματος σύγκρουσης μεταξύ δύο πλοίων έγινε υπό ανθρωποκεντρικό πρίσμα. Προκειμένου να πραγματοποιηθεί η απαιτούμενη ανάλυση, χρειάσθηκε πρώτα να γίνει μελέτη των μεθόδων που χρησιμοποιούνται για την έρευνα των συγκρούσεων πλοίων, καθώς επίσης και των παραμέτρων που εξετάζονται στις εν λόγω μελέτες. Η μελέτη των θαλασσίων συγκρούσεων καθιστά αναγκαίο τον ορισμό του όρου «περιοχή σύγκρουσης». Σημαντική κρίθηκε, επιπλέον, η εξέταση των παραγόντων που συμβάλουν στην πραγματοποίηση των θαλάσσιων ατυχημάτων. Έπειτα, ακολούθησε εκτενής παρουσίαση των απλών (simple) δικτύων Petri, μιας και αυτά αποτελούν την παρούσα μεθοδολογία ανάλυσης των συγκρούσεων πλοίων. Για λόγους πληρότητας επιπλέον αναφέρονται και οι υπόλοιποι τύποι των δικτύων Petri.

Στα πλαίσια της παρούσας διπλωματικής, κρίνεται σημαντική η αναφορά στους κανονισμούς που έχουν θεσπιστεί ανά τα χρόνια κι έχουν σκοπό την εδραίωση της ναυτικής ασφάλειας. Επειδή ο τύπος ναυτικού ατυχήματος που ερευνάται είναι οι συγκρούσεις, παρατίθενται επιπλέον πληροφορίες σχετικές με το κανονιστικό πλαίσιο συγκεκριμένα των συγκρούσεων πλοίων. Επιπλέον, αναγράφονται στοιχεία στατιστικής ανάλυσης των ατυχημάτων μεταξύ πλοίων. Τα στοιχεία αυτά αφορούν στο χρονικό πλαίσιο των τελευταίων δέκα ετών και σχετίζονται με τον συνολικό όγκο θαλασσίων μεταφορών, το είδος των πλοίων που εμπλέκονται στα ναυτικά ατυχήματα, τις ολικές απώλειες πλοίων και τη συμβολή του ανθρώπινου παράγοντα στην πραγματοποίηση των εν λόγω ατυχημάτων. Ακόμη, γίνεται επισκόπηση, ανάλυση και παρουσίαση των συνεπειών των θαλάσσιων ατυχημάτων (συνέπειες κοινωνικές, οικονομικές και συνέπειες που αφορούν σε καταστροφή της περιουσίας). Επίσης, για ιστορικούς λόγους, οι οποίοι εμπίπτουν στο πλαίσιο μελέτης της παρούσας διπλωματικής εργασίας, πραγματοποιείται παράθεση πληροφοριών σχετικών με ατυχήματα σύγκρουσης πλοίων που σημειώθηκαν τόσο κατά τον 20ο, όσο και κατά τον 21ο αιώνα.

Στο τελευταίο κομμάτι της εργασίας, παρουσιάζεται το μοντέλο Petri Net που αναπτύχθηκε. Το μοντέλο επεξηγείται πλήρως και σε βάθος, αναλύονται όλες οι

λεπτομέρειες που εμπλέκονται σε αυτό κι έπειτα περιγράφεται με σαφήνεια ο υπολογισμός της πιθανότητας σύγκρουσης. Το αποτέλεσμα συγκρίνεται με αντίστοιχους υπολογισμούς που υπάρχουν στη διεθνή βιβλιογραφία, σχολιάζονται κι επεξηγούνται οι πιθανές αποκλίσεις ή συγκλίσεις και προτείνονται διορθώσεις και ιδέες για μελλοντική έρευνα.

Στο $1^{ο}$ κεφάλαιο της διπλωματικής εργασίας πραγματοποιείται βιβλιογραφική επισκόπηση των παραμέτρων που χρησιμοποιούνται κατά την μελέτη των θαλάσσιων ατυχημάτων, όπως είναι, για παράδειγμα, τα σχεδιαστικά χαρακτηριστικά του πλοίου, τα χαρακτηριστικά ναυσιπλοΐας, η κατάσταση θάλασσας, οι καιρικές συνθήκες εργασίας. Επιπροσθέτως, γίνεται παρουσίαση και των διάφορων μεθοδολογιών που έχουν χρησιμοποιηθεί στο παρελθόν προκειμένου να γίνει η μελέτη των θαλάσσιων ατυχημάτων. Στη συνέχεια εξετάζεται η έννοια της «περιοχής σύγκρουσης», η οποία εξαρτάται από την απόσταση των πλοίων και το χρονικό διάστημα που μεσολαβεί από τη στιγμή που τα δύο πλοία θεωρείται ότι βρίσκονται σε πορεία σύγκρουσης, μέχρι να συμβεί το ενδεχόμενο ατύχημα σύγκρουσης. Ακολουθεί η βιβλιογραφική επισκόπηση των παραγόντων που συμβάλλουν στην πραγματοποίηση των θαλάσσιων ατυχημάτων, οι οποίοι μπορεί να συνδέονται τόσο με το εξωτερικό περιβάλλον του πλοίου, όσο και με το εσωτερικό, δηλαδή να αφορούν στα οργανωτικά ζητήματα του πλοίου. Κατά την αναφορά στους εσωτερικούς παράγοντες που ενδεχόμενα οδηγούν σε κάποιο ατύχημα μεταξύ δύο πλοίων, γίνεται ιδιαίτερη μνεία, όπως είναι αναμενόμενο, στη συμβολή του ανθρώπινου παράγοντα για τη συντέλεση του θαλάσσιου ατυχήματος.

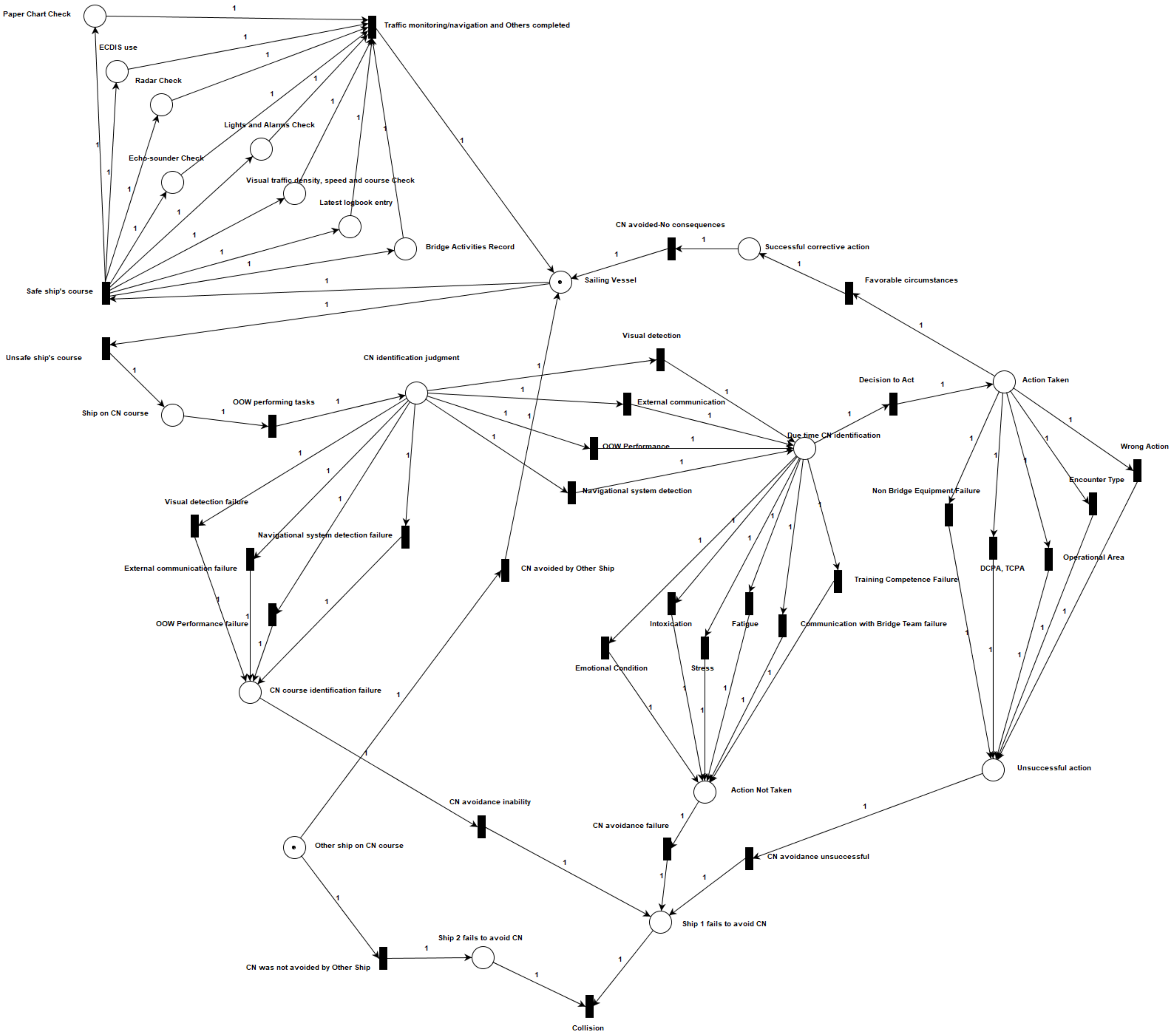
Στο $2^{ο}$ κεφάλαιο παρουσιάζονται τα δίκτυα Petri. Το μεγαλύτερο κομμάτι της εν λόγω παρουσίασης είναι αφιερωμένο στα απλά (simple) δίκτυα Petri, μιας και αυτά αποτελούν την παρούσα μεθοδολογία μελέτης της ενδεχόμενης σύγκρουσης μεταξύ δύο πλοίων. Τα απλά δίκτυα Petri είναι στατικά, δηλαδή δεν υπάρχει εμπλοκή της χρονικής παραμέτρου κατά τη μελέτη και ανάπτυξή τους. Για λόγους πληρότητας παρουσιάζονται και οι υπόλοιποι τύποι των δικτύων Petri, στους οποίους είναι δυνατή ή και δεδομένη η ανάμειξη της παραμέτρου του χρόνου. Κάθε τύπος δικτύου Petri απεικονίζεται με συγκεκριμένο τρόπο, ο οποίος και παρουσιάζεται για την κάθε περίπτωση. Για την ανάπτυξη, ωστόσο, όλων των τύπων δικτύων Petri υπάρχει μία κοινή βάση εργαλείων που παρουσιάζονται κι αξιοποιούνται και τα οποία αναφέρονται σαφώς στο κεφάλαιο αυτό.

Το $3^{ο}$ κεφάλαιο της παρούσας διπλωματικής εργασίας αφορά στους διεθνείς κανονισμούς και συμβάσεις που έχουν θεσπιστεί ανά τα χρόνια με σκοπό την εδραίωση της ναυτικής ασφάλειας. Παρουσιάζεται η ιστορική εξέλιξη της διαδικασίας θέσπισης των εν λόγω κανονισμών και συμβάσεων, αναφέρονται οι σημαντικότερες συμβάσεις της θαλάσσιας ασφάλειας, το περιεχόμενό τους και τα στάδια θέσπισής τους. Εξέχον ρόλο στο συγκεκριμένο κεφάλαιο παίζει η αναφορά συγκεκριμένα στους κανονισμούς αποφυγής σύγκρουσης, στην εξέλιξη εδραίωσής τους και ιδιαίτερα στο σχετικό ισχύον κανονιστικό πλαίσιο, που είναι οι Collision Regulations.

Στο 4ο κεφάλαιο, μέσω πινάκων και διαγραμμάτων, γίνεται η παρουσίαση διαφόρων στατιστικών στοιχείων που αφορούν στα θαλάσσια ατυχήματα και γενικότερα στις μετακινήσεις διά θαλάσσης. Τα στοιχεία που μελετώνται αναφέρονται σε δείγμα των τελευταίων 10 ετών. Σε αυτό το κεφάλαιο τονίζεται το γεγονός πως, τα τελευταία 10 χρόνια, ο πιο συχνός τύπος θαλάσσιου ατυχήματος υπήρξε η σύγκρουση μεταξύ δύο πλοίων. Επιπλέον, εξέχουσας σημασίας είναι και η υπογράμμιση των υψηλών ποσοστών συμβολής του ανθρώπινου παράγοντα στην συντέλεση των ναυτικών ατυχημάτων. Από τη μία η σπουδαιότητα του θαλάσσιου ατυχήματος της σύγκρουσης κι από την άλλη η εμπλοκή του ανθρώπινου παράγοντα στα ναυτικά ατυχήματα, θέτουν τους δύο βασικούς άξονες ανάπτυξης της παρούσας διπλωματικής εργασίας. Όλα τα στατιστικά στοιχεία που παρουσιάζονται στο 4ο κεφάλαιο σχολιάζονται.

Το 5ο κεφάλαιο της πτυχιακής εργασίας, συντέθηκε με αφορμή τον ορισμό των συνεπειών που προκύπτουν από τις συγκρούσεις μεταξύ των πλοίων: ανθρώπινος τραυματισμός ή ακόμη και θάνατος, απώλεια περιουσίας ή και περιβαλλοντική ζημιά. Έτσι, πραγματοποιείται μία σύντομη ιστορική παρουσίαση πραγματικών καταγεγραμμένων θαλάσσιων συγκρούσεων οι οποίες έλαβαν χώρα κατά τη διάρκεια του 20ου και του 21ου αιώνα κι οδήγησαν στην εκάστοτε κατηγορία συνεπειών. Στο συγκεκριμένο κεφάλαιο επιπλέον παρατίθενται και κάποιες φωτογραφίες που λήφθηκαν από καταγεγραμμένα ατυχήματα σύγκρουσης μεταξύ δύο πλοίων.

Στο 6ο κεφάλαιο γίνεται πλήρης ανάλυση και παρουσίαση του μοντέλου Petri Net που αναπτύχθηκε στα πλαίσια της παρούσας εργασίας. Συγκεκριμένα, για το αναπτυγμένο μοντέλο αναγράφονται κι εξηγούνται όλοι οι παράγοντες οι οποίοι λήφθηκαν υπόψιν και οι οποίοι θεωρείται ότι συντελούν στην ενδεχόμενη σύγκρουση μεταξύ δύο πλοίων. Επίσης, καταγράφονται αναλυτικά και τα καθήκοντα του αξιωματικού γέφυρας, ο οποίος θεωρείται ότι βρίσκεται σε πορεία εκτέλεσής τους σε διάφορα στάδια της πορείας σύγκρουσης. Ολόκληρο το μοντέλο Petri έχει χτιστεί λαμβάνοντας τον ανθρώπινο παράγοντα ως τον κυριότερο παράγοντα πραγματοποίησης της σύγκρουσης, για αυτόν τον λόγο και, όπως έχει αναφερθεί ήδη, η εξέταση του ενδεχόμενου ατυχήματος αποτελεί ανθρωποκεντρική ανάλυση. Φυσικά, αξίζει να σημειωθεί ότι ο ανθρώπινος παράγοντας δεν είναι ο μοναδικός παράγοντας που μπορεί να οδηγήσει στην πραγματοποίηση ενός ατυχήματος σύγκρουσης αλλά και κάθε άλλου είδους θαλάσσιου ατυχήματος. Ωστόσο, στα πλαίσια της συγκεκριμένης πτυχιακής εργασίας, το βάρος συντέλεσης της σύγκρουσης εναποτίθεται σχεδόν αποκλειστικά στον αξιωματικό γέφυρας, δηλαδή στον ανθρώπινο παράγοντα. Στο σχήμα της επόμενης σελίδας, για λόγους πληρότητας, κρίθηκε σκόπιμο να παρουσιασθεί το μοντέλο δικτύου Petri που χτίσθηκε στα πλαίσια της συγκεκριμένης πτυχιακής εργασίας.


Paper Chart Check
Traffic monitoring/navigation and Others completed
ECDIS use
Radar Check
Lights and Alarms Check
Echo-sounder Check
Visual traffic density, speed and course Check
Latest logbook entry
Bridge Activities Record
CN avoided-No consequences
Successful corrective action
Safe ship's course
Sailing Vessel
Favorable circumstances
Unsafe ship's course
Visual detection
CN identification judgment
Decision to Act
Action Taken
Ship on CN course
OOW performing tasks
External communication
Due time CN identification
OOW Performance
Wrong Action
Encounter Type
Non Bridge Equipment Failure
Navigational system detection
Visual detection failure
Navigational system detection failure
External communication failure
CN avoided by Other Ship
DCPA, TCPA
Operational Area
Training Competence Failure
OOW Performance failure
Intoxication
Fatigue
Communication with Bridge Team failure
Emotional Condition
Stress
CN course identification failure
Unsuccessful action
Action Not Taken
CN avoidance inability
CN avoidance failure
Other ship on CN course
CN avoidance unsuccessful
Ship 1 fails to avoid CN
Ship 2 fails to avoid CN
CN was not avoided by Other Ship
Collision

Στο 7ο κεφάλαιο της παρούσας διπλωματικής εργασίας, με βάση το μοντέλο του δικτύου Petri που έχει ήδη παρουσιαστεί στο προηγούμενο κεφάλαιο, υπολογίζεται αναλυτικά η πιθανότητα σύγκρουσης. Προκειμένου να γίνει ο εν λόγω υπολογισμός, πραγματοποιείται αξιοποίηση επιμέρους πιθανοτήτων διαφόρων παραγόντων που βρέθηκαν στη βιβλιογραφία. Αυτό συμβαίνει, καθώς ο τελικός υπολογισμός της πιθανότητας σύγκρουσης αποτελεί μαθηματική συνάρτηση άλλων πιθανοτήτων που εμφανίζονται κατά την πορεία εξέλιξης του ατυχήματος σύγκρουσης. Οι πιθανότητες αυτές είναι ουσιαστικά η ποσοτικοποίηση συγκεκριμένων γεγονότων, τα οποία συντελούν στην πραγματοποίηση του αναφερθέντος ατυχήματος.

Το 8ο κεφάλαιο αποτελεί το τελευταίο κομμάτι της συγκεκριμένης πτυχιακής εργασίας. Σε αυτό το κεφάλαιο λοιπόν, γίνεται σύγκριση του αποτελέσματος, δηλαδή της υπολογισθείσας πιθανότητας σύγκρουσης μεταξύ δύο πλοίων, με αντίστοιχα νούμερα που έχουν υπολογισθεί στο παρελθόν σε αντίστοιχες έρευνες και υπάρχουν στη διεθνή βιβλιογραφία. Στους πίνακες που ακολουθούν παρουσιάζονται συνοπτικά τα αποτελέσματα πιθανότητας που προέκυψαν από το αναπτυγμένο μοντέλο δικτύου Petri κι έπειτα τα αντίστοιχα αποτελέσματα που βρέθηκαν στη διεθνή βιβλιογραφία. Στο αναφερθέν αυτό τελευταίο κεφάλαιο, αφού παρουσιασθούν τα εν λόγω αποτελέσματα, σχολιάζεται το αποτέλεσμα που προέκυψε, τεκμηριώνονται οι τυχόν αποκλίσεις με αντίστοιχους υπολογισμούς και, τέλος, παρουσιάζονται προτάσεις για μελλοντική έρευνα.

Αποτελέσματα υπολογισμών μοντέλου Petri Net	
Χαρακτηριστικό	Τιμή Πιθανότητας
Μετωπική σύγκρουση	1.44E-05
Σύγκρουση διασταυρούμενης πορείας	2.21E-05
Σύγκρουση κατά την προσπέραση	1.52E-05

Διεθνής Βιβλιογραφία		
Χαρακτηριστικό	Τιμή Πιθανότητας	Πηγή
Ρηχά κι επικίνδυνα νερά	1.08E-04	(Mulyadi et al., 2014)
Γενικευμένο μοντέλο	2.1E-05	(Sotiralis et al., 2016)
Κρουαζιερόπλοιο	8.6E-06	(Det Norske Veritas, 2002)
Μετωπική σύγκρουση	4.96E-05	(Przywarty et al., 2015)
Σύγκρουση διασταυρούμενης πορείας	5.6E-05	
Σύγκρουση κατά την προσπέραση	3.98E-05	

Abstract

The purpose of the present thesis is the calculation of the vessel collision probability, which is conducted by the anthropocentric analysis of a potential collision accident. This calculation was made by using Matlab and the platform Petri Net Editor (PIPE), which, as its name indicates, is a useful tool for designing and studying Petri Nets.

In order for the required analysis to be conducted, the study of the methods that are used for the vessel collision research, as well as the study of the parameters that are considered in the aforementioned research are initially necessary. The definition of the term "collision area" is of great significance in order to study the vessel collision accident. It is also important to investigate the factors that contribute to the occurrence of shipping accidents and, in particular, the human factor. Then, an extensive presentation of the simple Petri Nets is made, as this kind of Petri Nets are the present methodology for analysing ship collisions. For completeness reasons, the other types of Petri Nets are also mentioned.

In the context of the present thesis, the reference to the rules and regulations that have been adopted over the years, aiming at the maritime safety consolidation, is very important. However, the type of shipping accident that is studied is the collision, and thus, information specifically relevant to the vessel collision regulatory framework is given. In addition, data of statistical analysis of accidents between ships are provided. The statistical data that are indicated concern the period of the last ten years and are about the total volume of sea transportation, the type of vessels involved in the shipping accidents, the vessel total losses and the human factor contribution to the realization of the aforementioned casualties. A review, analysis and presentation of the consequences of shipping accidents (social, economic and property-related consequences) is also made. Moreover, information about vessel collision accidents that occurred during both the 20th and the 21st century is provided.

In the last part of the thesis, the developed Petri Net model is presented. The model is fully explained, all the involved details are analysed and then the collision probability calculation is described. The result is compared with corresponding calculations that exist in the literature and furthermore, comments, ideas and suggestions for future work are presented.

In the 1st chapter, a literature review is made, which concerns the parameters and the methodologies that are used for the study of shipping accidents, the collision area and the factors that contribute to the shipping accidents. In the literature review, more specifically the contribution of human factor to the aforementioned accidents is concerned.

In the 2nd chapter, Petri Nets are presented. Simple Petri Nets are more extensively mentioned, as they constitute the current methodology for studying the potential collision between two vessels.

The 3rd chapter is about the regulatory framework for collisions between ships and in particular, the evolution of the relevant rules and regulations that have been adopted over the years is mentioned. The presentation of the current regulatory framework, which is the Collision Regulations, is very important in the specific chapter.

In the 4th chapter, tables and diagrams that concern the shipping accidents statistics are presented. The aforementioned statistical data are also analysed.

In the 5th chapter, the definition of the consequences of collisions between vessels is given and then, actual recorded collision occurrences between ships are presented. These accidents have led to one or more consequences, which come under a shipping accident consequence category.

The 6th chapter presents a full analysis of the Petri Net model that was developed in the context of the present thesis. More specifically, the factors that contribute to the potential collision between two ships, as well as the duties of the Officer of the Watch are listed and explained. The whole model has been developed taking the human factor as the main cause of the collision and thus, the research of the potential accident constitutes an anthropocentric analysis.

In chapter 7, according to the -already presented- Petri Net model, the collision probability is analytically calculated, recovering individual probabilities of different factors that were found in the literature.

In chapter 8, the result is compared with the corresponding numbers that exist in the literature and suggestions for future work are presented.

1. Literature Review

1.1. Parameters Studied in Vessel Collision Examination

Throughout research process, numerous parameters that are involved in vessel collision examination were identified and are listed below.

Often used parameters are the design features of the vessel which are involved in the encounter situation, such as the length and breadth of the ship (Goerlandt and Kujala, 2011; Montewka et al., 2013; Rakas, 2015; Xu et al., 2014). Navigation characteristics of the vessel, such as her speed, her position, and the encounter angle (Eriksen and Breivik, 2017; Goerlandt and Kujala, 2011; Kiriyama et al., n.d.; Samuelides et al., 2008) are three parameters of crucial importance that are being considered, together with Distance at Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA). As it is easily understood, the latter two parameters indicate a great dependency on the top three mentioned parameters. Sea state (Xu et al., 2014) and working conditions, such as the time of the day, the weather and atmosphere on the vessel (Sotiralis et al., 2016) are some other significant parameters which appear in papers that study collisions between vessels.

The parameterization of human factor is, although very complicated, essential. It is worth noting that, statistically it has been found that human error is implicated at a percentage of 75-96% of marine casualties that have occurred (Hetherington et al., 2006; Kiosses, 2015; Lloyd’s Maritime Academy, n.d.; Matsidi, 2014; Rothblum, 2000). The person who is basically involved in the management of the collision situation (detection, action, avoidance) is the officer of the watch (OOW) and thus, the whole analysis is actually done around him (Deligiannis, 2017; Sotiralis et al., 2016). There are numerous factors, connected with human existence, electronic systems and the interaction between them that affect the human performance. Some of the aforementioned factors are the internal and external communication, the organizational factors and the human perception (Martins and Maturana, 2013). It is clear that, fatigue, stress, emotional condition, training competence and intoxication are factors that contribute to human perception. The sufficiency of non-bridge equipment (the steering system) and navigational systems (ECDIS, Paper Chart, Radar, GPS) (Det Norske Veritas, 2006), together with human interaction with them are of great significance as well. The performance of the OOW is also affected by the bridge layout and the working conditions (time of the day, weather and atmosphere on the vessel). The quantification of the aforementioned parameters is an important issue. However, the connection of the parameters with human factor and especially with the performance of the OOW, makes the requested quantification a very difficult procedure.

1.2. Methodologies Followed in Vessel Collision Examination

In order to study the occurrence of vessel collision, numerous methodologies are being examined and developed within the scientific and working community. Below, the methodologies that are being used are synoptically presented.

One of the most common methodologies is the analytical method of the Fault Tree Analysis (FTA) which is the evolution of a physical system into a structured logic diagram (Lee, 1985) and the involved events are related by terms of cause-and-effect (Liu and Chiou, 1997). In the paper of Martins and Maturana (Martins and Maturana, 2010) human error contribution analysis is done for the case of collision and/or grounding of tankers at the Brazilian coast, using the FTA so as to estimate the causation probability of the collision event. Similarly, in the work of Uğurlu et al. (Uğurlu et al., 2015), a calculation of the collision probability is carried out regarding different factors.

The construction of a FT might be a stringent procedure when it comes to considering numerous events (Chen et al., 2019). Ship collision research process is also served by the use of Bayesian Networks (BNs). BNs are directed acyclic graphs with nodes that represent a set of random variables and their optimal dependencies (Philippi et al., 2006; Sotiralis et al., 2016). Montewka et al. (Montewka et al., 2013) use the BNs methodology to perform a study in the Gulf of Finland during the ice-free period and assess the probabilities of the events coming after a ship-ship collision. Martins and Maturana (Martins and Maturana, 2013) evolve their study (Martins and Maturana, 2010) and analyze human reliability with BNs. This methodology is also met in the work of Sotiralis et al. (Sotiralis et al., 2016). Leading factors to human performance during collision accidents are identified and a collision risk assessment is accomplished through probabilistic analysis.

Another methodology that is often preferable is the Event Tree (ET) Analysis. An ET is a logic diagram and reveals the probability or the frequency of an accident (Rakas, 2015). It starts with a specific event (initiating event) and finishes with all the possible outcomes (Nývlt et al., 2014). Probabilistic determination of the events involved in the FT of Martins and Maturana (Martins and Maturana, 2010) was aided by the results obtained from an ET. In the work of Ali and Haugen (Ali and Haugen 2012) an ET is used to examine a potential collision state of a supply vessel probabilistically. The aforementioned ET is also presented in the study of Nývlt et al. (Nývlt et al., 2014), where it is simplified for the purposes of the paper.

Ship Collision accidents might be as well analysed by the use of Fuzzy Inference Systems. The Fuzzy Inference Systems are based on rules that codify the accumulated expert knowledge and are preferably used in cases of complicated problems (Rakas, 2015). In the paper of Qu et al. (Qu et al., 2011), three ship collision indices are introduced to complete the collision risk assessment. The study is conducted for the Singapore Strait. Wang et al. (Wang et al., 2013) implement fuzzy set methods to evaluate the quality of the actions taken during the collision avoidance process. The potential encounter situation is studied within the area of the Yangtze River, China. Su et al. (Su et al., 2012) accomplish their research for the coast of Keelung harbor, Taiwan, and present a Fuzzy Monitoring System, according to which, collision avoidance activities are suggested.

Very often the collision course is simulated so as to get more realistic and quantified results. For the purposes of this process vessel's design features (length, breadth) and navigation characteristics (speed, position, encounter angle), sea state or working conditions (time of the day, weather, atmosphere on the vessel) are analysed. Montewka et al. (Montewka et al., 2010) work with the Monte Carlo simulation to calculate the geometrical probability of potential collisions in the Gulf of Finland. The Monte Carlo simulation is also chosen in the work of Goerlandt et al. (Goerlandt et al., 2012). Within the paper, a risk assessment is performed about collisions happening in the Gulf of Findland. Other researchers practice the Nomoto model. In the work of Xu (Xu, 2014) the aforementioned model is used to simulate the studied vessel and to develop the best possible collision avoidance strategy. In the research of Li and Pang (Li and Pang, 2013) a collision situation is simulated and the Dempster-Shafer (D-S) evidence theory is used so that the collision risk might be calculated.

A methodology that could be used in order to study vessel collision is the Petri Net (PN) analysis. The PN methodology has been used mostly in scientific fields, other than maritime, such as biology (Chaouiya, 2007; Sackmann et al., 2006), robotics (Costelha and Lima, 2012) and computation (Marsan et al., 1984). However, a restricted number of researchers has chosen PNs for the purposes of ship collision investigation. In the work of Nývlt et al. (Nývlt et al., 2014) an ET was tranformed into a PN and the study was about collision accidents that occur between vessels laid near the shore and coastal facilities.

1.3. The Collision Area

Two of the most important parameters that should be considered in order to study collision between two vessels more accurately are the distance between the vessels that are about to collide and the time that mediates, from the moment the vessels are on a collision course until the predicted moment of collision. The aforementioned parameters are the formation basis of the "Risk of Collision". The "Risk of Collision" is considered to exist, only when the DCPA is smaller than a specific, secure distance between the vessels, and when there is not enough TCPA ahead. The COLREGs convention refers to the "close-quarters situation", which is the state under which the vessels that are about to collide have reached a very small, dangerous relative distance and, unless both ships act accordingly, it will not be possible to avoid collision (Hao and Zhao, 2019). However, the COLREGs do not clearly provide information about distance limits, but there are numerous studies that, considering the Convention, refer to measured parameters which describe the area of collision (Hilgert and Baldauf, 1997).

It is obvious that, the closer they are one to another, the higher the collision probability it gets (Zhang et al., 2012). Ships are solid bodies and not points, and thus, the “Distance to Collision” is actually a domain of a non-stable form (Davis et al., 1980) that depends on numerous parameters and factors. Over the years, this collision domain has been studied by numerous researchers, who have assigned different forms to the domain (He et al., 2017).

Montewka et al. (Montewka et al., 2011) define the meaning of minimum distance to collision (MDTC) and support that, the elements that influence this parameter are the vessels’ type, the vessels’ relative course angle and the vessels’ voyage plan. However, in the aforementioned paper of Montewka et al., it is highlighted that, the position of two vessels that are in a collision course, is considered to be critical, when the vessels are 0.5 NM apart. The same critical distance between the vessels that are about to collide is proposed in the paper of Goerlandt and Kujala (Goerlandt and Kujala, 2011).

In the research of Zhang et al. (Zhang et al., 2012) different potential collisions are simulated, in order to examine the factors (vessels’ size, velocity, starting points and relative angles) under which a safe distance for collision avoidance is ensured. In the study of Krata et al. (Krata et al., 2016), the safe area for collision avoidance is determined. In the context of the aforementioned determination, changes in the turn of the rudder (from 5° to 30° with a step of 5°) and particular sea state, vessel and encounter type are considered. Yim et al. (Yim et al., 2018) study five possible relative angles of approach, from 0° to 180° with a step of 45° and 12 possible lengths of approach, from 0.25 NM to 3 NM with a step of 0.25 NM.

In the research of Hao and Zhao (Hao and Zhao, 2019) the collision area is considered as a multiparametric factor. In the aforementioned paper, specific minimum distances for feasible collision avoidance are listed, which are based on different researches. The minimum collision avoidance distances depend on the encounter type (head-on, crossing, overtaking), the state of visibility, the operational area, the relative velocity of the vessels etc. It is concluded, however, that an average minimum distance of 1 NM should be kept in all cases.

According to Koldemir (Koldemir, 2009), the “Risk of Collision” is separated into categories and exists only when the distance between the vessels that are about to collide is less than 3 NM. A distance greater than 3 NM is not considered to impose the vessels to remarkable risk, while a distance equal to or less than 1 NM is considered as the limit distance, according to which the risk gets the critical characterization “imminent”.

1.4. Leading Factors for Vessel Collision

There are numerous factors that contribute to vessel collision realization. The determination of the collision hazards is a very important procedure and it is the first step of any Formal Safety Assessment (FSA) (Marine Insight, 2019a) that calculates the risk of ship collisions.

The vessel's safety is affected by both external factors and internal factors, connected with the organisation of the ship. External factors are the environmental factors: Wind, visibility and currents (Shu et al., 2017). The organisational factors that might induce the collision accident are grouped into four main categories, according to Geijerstam and Svensson (Geijerstam and Svensson, 2008):

a. Deliberate damage
b. Technical difficulties
c. Lack of awareness and
d. Manipulation mistakes

Deliberate damage is caused by a person who is on the vessel and on purpose provokes the collision. For example, a collision that accrues from an event of terrorism is a deliberate damage. It is obvious, that the aforementioned example of collision does not constitute an accident.

Technical difficulties include problems that might arise when the technical equipment of the ship (the steering system and the navigational systems-ECDIS, Paper Chart, Radar, GPS) suffers a total or partial failure. The person who is in charge of the vessel's safety and course, the OOW, has, in that case, recognised the development of the collision situation but is unable of changing it.

Lack of awareness means that the OOW has not identified the forthcoming collision, but manipulation mistakes are wrong actions, taken after the collision course has been identified. The latter two categories happen both due to reasons that are basically connected to the OOW's personal state (fatigue, stress, emotional condition, training competence and intoxication) and lead to collision avoidance failure. The human factor has been concerned by the shipping scientific community numerous times and very often it has been studied and analysed.

2. Methodology

2.1. Introduction

As it has already been highlighted, PNs do not constitute a methodology that has been used frequently to study maritime issues and thus, the development of a PN which deals with the study of vessel collision accidents, is an innovation. In this paper it was decided that vessel collision probability will be calculated by using a PN model. PNs are suitable for probability calculation, as it is indicated in the research of Philippi et al. (Philippi et al., 2006). In the developed model, the collision accident is anthropocentrically analysed, and, apart from the probability determination, the series of events that lead to collision is presented.

2.2. Simple (original) Petri Nets

The conception of PNs was made by Dr. Carl Adam Petri in 1962 (Wang, 2007). PNs represent a graphical modeling tool with strong mathematical structure (Nývlt et al., 2014). They are used to analyze Discrete Event Systems and their applications have faced numerous scientific fields such as biological and medicine sciences (Sackmann et al., 2006), molecular networks (Chaouiya, 2007), robotics (Costelha and Lima, 2012), energy flexibility (Graßl et al., 2014), wind turbine modeling (Le and Andrews, 2015) etc.

PNs represent complex systems and consist of places, transitions, tokens and arcs. More specifically, places are connected to transitions through directed arcs and vice versa. Places have cyclic or oval shape, transitions are represented by a bar or a rectangle and arcs are, in essence, arrows. Each place may contain one or more tokens, each of them designed as a dot (Liu and Chiou, 1997). A place filled with tokens represents an activated state, or, in other words, it indicates that the attached condition is real (Wang, 2007).

Each arc has, by default, capacity equal to 1, which means that it might transfer only one token from a place to a transition or from a transition to a place. If an arc's capacity is differentiated, this is clearly stated on the arc (Petri, 1962). A transition is able to fire only when in all of its input places exists a number of tokens equal to at least the weight of the connecting arc. If a transition fires, tokens are transferred to its output places, according to the arc weights (Liu and Chiou, 1997). This means that, if the capacity of the arcs within a Petri Net remains the same, tokens seem to be moving across the transition. However, if the capacity of the arcs of a specific Petri Net changes, tokens might be created or destroyed (Petri, 1962).

The following examples are presented for clarifying reasons. Red colored are the transitions that are ready to fire.

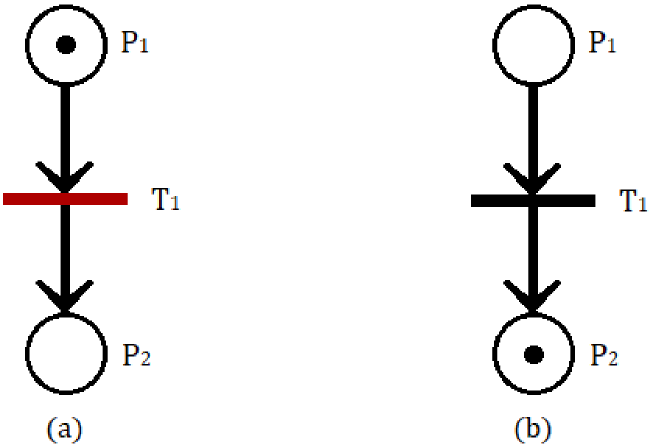


Figure 2.1: A simple Petri net with arcs of capacity 1 (a) Before the firing of T_1. (b) After the firing of T_1.

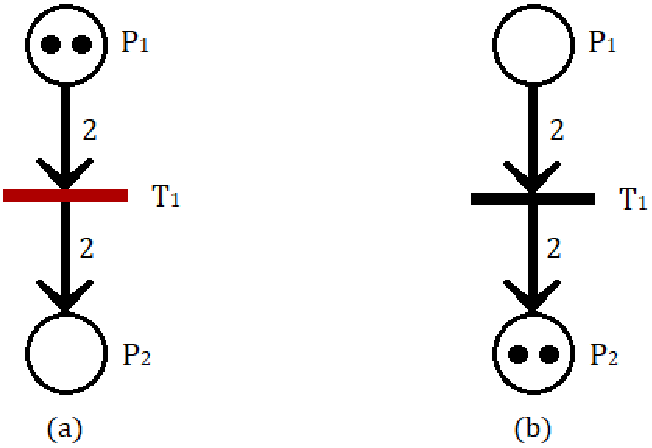


Figure 2.2: A Petri net with arcs of capacity 2 (a) Before the firing of T_1. (b) After the firing of T_1.

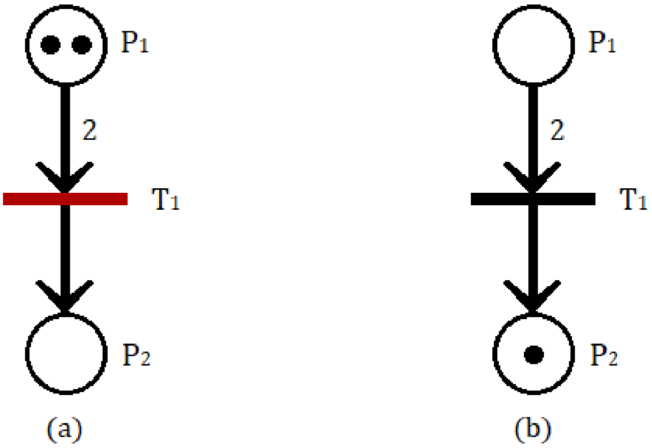


Figure 2.3: A Petri net with arcs of capacity that changes along the net (a) Before the firing of T_1. (b) After the firing of T_1.

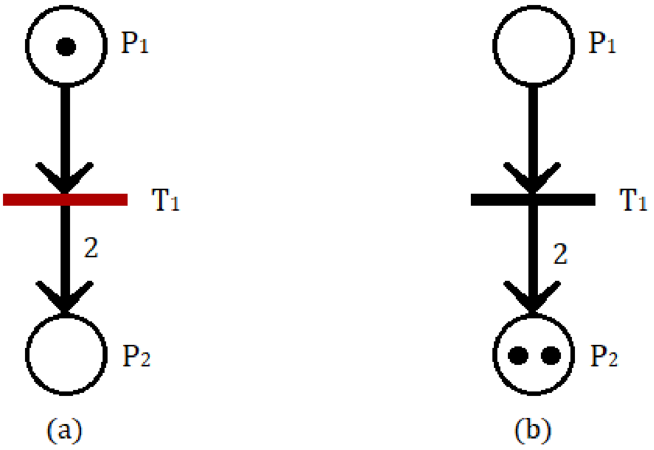


Figure 2.4: A Petri net with arcs of capacity that changes along the net (a) Before the firing of T_1. (b) After the firing of T_1.

At this point it is worth noting that there is a particular kind of arc, the inhibitor arc, according to which, the firing enablement of a transition happens only if no tokens exist in the input place. The inhibitor arc does not have the shape of an arrow, instead it is a cycle at the end of a line. In the figures below, the operation of the inhibitor arc might be clearly understood.

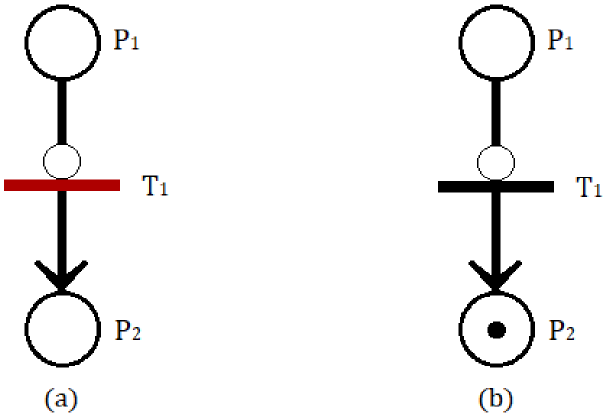


Figure 2.5: A Petri net with an inhibitor arc (a) Before the firing of T_1. (b) After the firing of T_1.

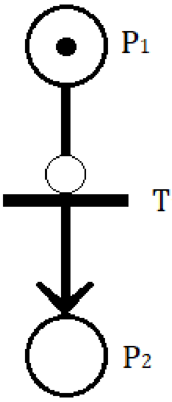


Figure 2.6: A Petri net with an inhibitor arc. Transition T_1 is not able to fire, due to the fact that a token exists in place P_1.

Over the years, Petri Net theory has evolved. The graphical representation of PNs might be pretty hard when the studied model becomes complicated and extensive and thus, new types of PNs are raising. The new types of PNs are listed and shortly analysed below.

2.3. Coloured Petri Nets

Coloured Petri Nets (CPNs) were introduced by Kurt Jensen in 1981 (Jensen, 1981) and are widely used since then. They form a modeling language that is used for designing, simulating and analyzing systems. CPNs aim to the construction of a solid parametrised model (Jensen and Kristensen, 2009).

Places, transitions, arcs and tokens appear in CPNs as well as in the original PNs. Programming expressions are stated on the arcs and thus the tokens of the input places are provided with specific properties (Chaouiya, 2007). The concept of a CPN is attached to the separation of tokens according to their colours. In a CPN similar data types are considered as a unit and are coloured with a specific color set. Colour sets are related to places and transitions. The firing priority of a transition depends on the attached colour set. By incorporating color sets, the consolidation of structures of common interest within the network is feasible and the structure of the network becomes distinct (Blätke et al., 2015).

In Figure 2.7 that follows, the transformation of a simple PN (Figure 2.7 a) into a CPN (Figure 2.7 b) is presented (Wang, 2007). Both the simple PN and the CPN represent a model of a manufacturing system. The CPN has the number of transitions and places clearly diminished, compared to the placed and transitions that appear in the simple PN. The aforementioned reduction happens, due to the fact that, as it has already been mentioned, in CPNs similar data types are considered as a unit and are grouped. Colour sets are also involved in the CPN model. In figure 2.7, each place and transition that appears in the CPN (Figure 2.7 b) corresponds to specific places and transitions of the simple PN (Figure 2.7 a). The transformed CPN model is a solid PN model of reduced size and complexity.

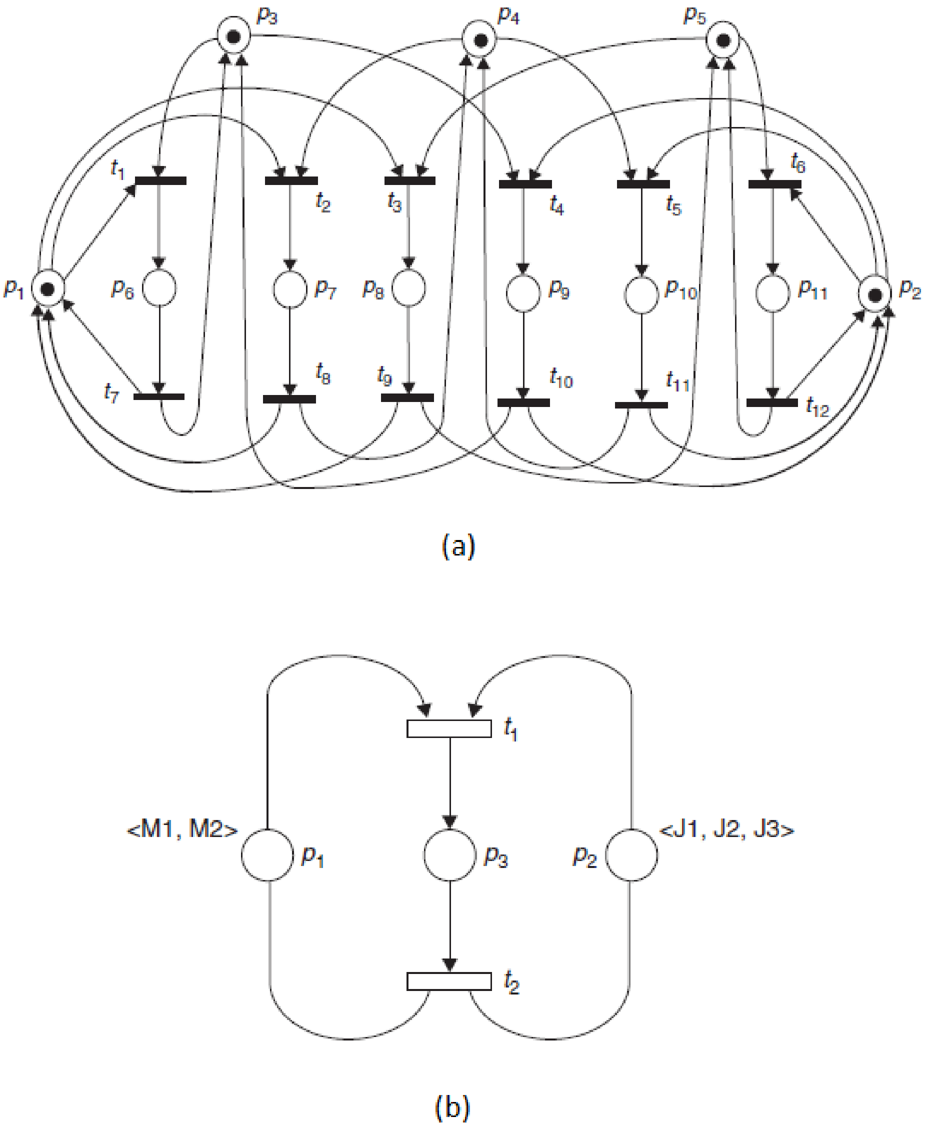


Figure 2.7: A manufacturing system (a) presented by a simple PN model (b) presented by a CPN model

Another characteristic of CPNs is that they might enrich transitions with time variables (Blätke et al., 2015). Petri Nets that consider the parameter of time are analysed below.

2.4. Timed Petri Nets

Real life problems are time-attached and, in order for a Petri Net model to be formed realistically, the establishment of time variables is essential. When done so, the Petri Net is called Timed Petri Net (TPN) (Wang, 1998). Transitions, places, tokens and arcs do not miss from TPNs. The difference between the original PNs and TPNs lies in the fact that the transfer of tokens happens with respect to the firing time (Wang, 2007). TPNs are separated into two basic categories: the Deterministic Petri Nets (DPNs) and the Stochastic Petri Nets (SPNs) (Wang, 1998).

2.4.1. Deterministic Petri Nets

DPNs were initially studied by Guy Vidal-Naquet in 1980 (Pelz, 1987), but Ramchandani, in 1974, had already tried to insert constant time labels into PN modelling (Wang, 2007). The application field of DPNs meets the needs of real-time problems. Places, transitions, arcs and tokens exist in DPNs, but the difference with original PNs is the fact that a number equal or bigger than zero is attached to each transition, and, in that way, deterministic firing time gets involved (Wang, 1998; Zuberek, 1991). Deterministic firing time forces the transition that is ahead of time to be executed first. In other words, a time priority in the firing of transitions is adhered (Ciardo and Lindemann, 1993).

Figure 2.8 depicts a model of a DPN. As it might be easily noticed, constant (deterministic) firing times are assigned to the transitions of the DPN model, which are noted below each of the transitions t_1, t_2, t_3, t_4, t_5, t_6 and t_7. The following PN also involves probabilistic characteristics connected with place p_3 and an inhibitor arc that comes after place p_6.

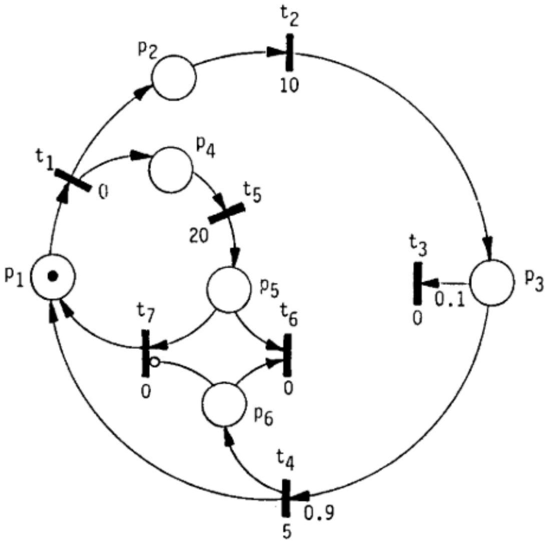


Figure 2.8: An example of a DPN (Zuberek, 1991)

2.4.2. Stochastic Petri Nets

The construction of SPNs is based on the one of the original PNs. SPNs consist of places, transitions, arcs and tokens and the connection of them all is as it has been described already. SPNs belong to TPNs, which means that, in contrast to the original PNs, time is involved in the execution of the net. A specified stochastic waiting time for each transition should elapse, in order for the transition to be finally able to fire (Blätke et al., 2015). The firing time of each transition is a random variable serving a negative exponential probability distribution. In other words, there is a firing rate attached to each transition existing in the SPN, which is the parameter of the aforementioned exponential distribution.

The following figure (Figure 2.9) is a depiction of a SPN. The parameters λ, μ, α and β are all exponential parameters.

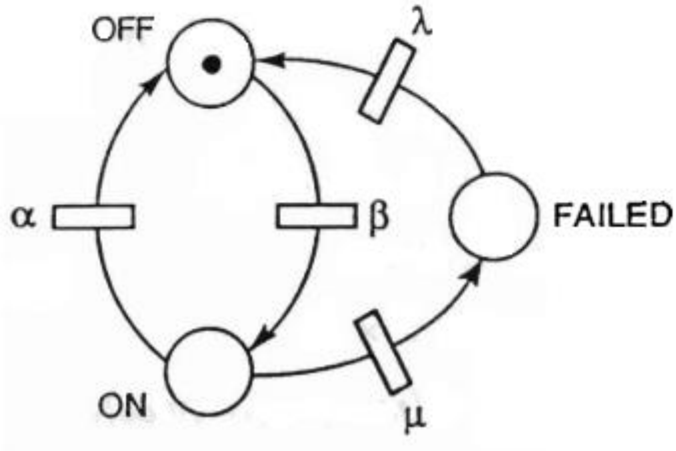


Figure 2.9: A SPN model (Marsan, 1990)

One thing that might restrict the use of SPNs is the fact that, their study might present obstacles, as the model gets wider or more complicated. The difficulty of their research is faced by the use of Generalised Stochastic Petri Nets (GSPNs) (Marsan, 1990).

2.4.2.1. Generalised Stochastic Petri Nets

GSPNs were initially studied by Marco Ajmone Marsan, Gianfranco Balbo and Gianni Conte in 1984 (Marsan et al., 1984). With GSPNs the use of transitions gets expanded: apart from the existence of timed, exponentially attached transitions that present in SPNs, immediate transitions are introduced as well. The latter mentioned transitions have a firing priority and the time borders do not affect their execution.

Another innovation of the GSPNs is the depiction of the different kinds of transitions, as timed transitions are designed as black or white orthogonal boxes and immediate transitions as narrow boxes that are similar to a line (Marsan, 1990). An example of GSPNs illustration is cited in Figure 2.10.

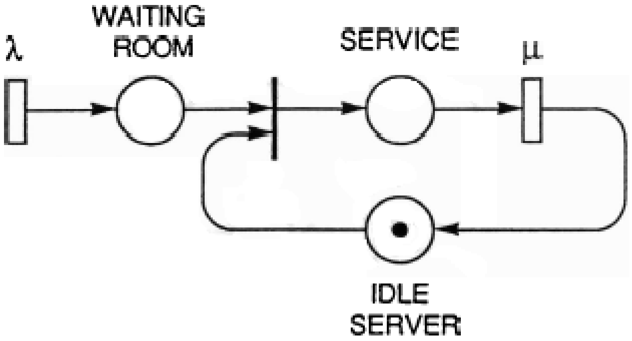


Figure 2.10: A GSPN model, where timed transitions are designed as white orthogonal boxes and immediate transitions as a black line.

Inhibitor arcs facilitate the setup and execution of GSPNs and their use is expanded (Marsan et al., 1984). The application of inhibitor arcs has already been described above.

3. Regulatory Framework

3.1. Introduction

The shipping industry is one of the most heavily regulated industries, enhanced with numerous international safety regulations, with respect to the protection of the environment, the human life and the property. Since 1958, the International Maritime Organisation[1] (IMO) has been dealing with the regulation of the maritime safety issues (Veiga, 2002). Numerous rules and regulations had been adopted before the formation of the IMO, but, until the first decades of the 20th century, all of them were actually a sum of informal conventions and procedures, rather than officially enacted treaties. The term "safety at sea" consists of three main pillars, the three most important maritime conventions, according to the IMO: the SOLAS convention, which concerns the safety of life, the MARPOL 73/78 convention, which concerns the safety of the oceanic environment and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW).

In the following sections, the informal rules and regulations that constitute the origin of the maritime safety system are presented, together with the STCW, the history of the SOLAS convention and the MARPOL 73/78 convention. However, as it has been already been highlighted, the present thesis specifically studies the accident of collision between two vessels. Thus, at the end of the current chapter, a more extensive part is devoted to the collision regulations that have been established over the last decades. As the collision regulatory framework that is in force nowadays is the COLREGs, a special reference is made to it.

3.2. The evolution of the maritime safety system

Maritime safety is a serious issue, although very complicated, and it is closely connected with the existence and activities of human beings (Veiga, 2002). It is very important, thus, the record and implementation of regulations which concern the maritime safety assurance. However, shipping industry is characterised as "reactive", which means that, in order to take a safety measure, an accident should have been preceded. This philosophy has not helped the prevention of shipping accidents so far and it makes the safety establishment a very slow procedure (Keefe, 2014; Oltedal and Lützhöft, 2018).

Before any formal maritime accident regulation was ever established, numerous conventions and informal procedures existed, which led to various disputations and

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[1] The Inter-governmental Maritime Consultative Organisation (IMCO), the specialised agency of the United Nations, was set up in 1948 and entered into force in 1958. However, in 1982, the organisation changed its name to International Maritime Organisation (IMO) (Blanco-Bazán, 2004).

unplanned casualties. The first effort to manage the maritime safety was made a few decades after the beginning of the 19th century and, since then, this process of safety establishment attempts has not been ever ceased.

In 1838, the “Steamboat Act” was adopted, according to which every steamboat should be inspected under a frequency of half a year. In 1840, the London Trinity House composed an amount of safety regulations which were approved by the Parliament in 1846 (Cockcroft and Lameijer, 2003). The same year, the “Steam Navigation Act” was adopted, which included some regulations regarding lights for steam ships (Pike, 2018). These regulations were enhanced in 1849 and in 1850 English maritime law drew some speed and distance sailing limits.

It was widely accepted that no substantial safety measures for merchant vessels had been taken up to then, and the large amount of recorded shipping accidents and deaths was alarming. However, the attempts to establish maritime safety continued. The year 1867, Thomas Gray composed a brochure of useful naval assistance, which became famous and is still cited in some books (Cockcroft and Lameijer, 2003). In 1873, a general demand of cargo limits determination arose, due to the fact that many seamen had lost their lives while traveling on overload vessels (Talley, 2008). In 1876, the load line mark, known as the Plimsoll line, was made compulsory by the British Merchant Shipping Act, but the exact position of the mark was legislated later on (Jones, 2007). 1876 was the year that the United Kingdom introduced the inception of the Port State Control as well.

In 1884, some new safety regulations were adopted but no significant change was made, compared to the already enacted rules and regulations. In the International Maritime Conference of 1889, a number of new regulations were instituted, which concerned the actions of the stand-on and the giving-way vessel, as well as the lights restrictions of the steamships. The aforementioned conference is known as the Washington Conference. Later on, the “Merchant Shipping Act of 1894” was adopted by the United Kingdom. This Act dealt with almost every issue concerning the maritime safety of that time, including the official documents of people working onboard (Veiga, 2002) and the legislation of the Plimsoll loading line.

Although the recorded efforts to establish safety standards were numerous, it is a fact that, since the decade of 1860, only minor changes to the already adopted rules and regulations had been made. However, at a Conference in London, 1914, the first version of the Safety of Life at Sea (SOLAS) Convention was eventually adopted.

3.3. The SOLAS Convention

The most important maritime convention is the SOLAS convention, which, as its name indicates, concerns the safety of life at sea. The SOLAS convention is a worldwide shipping agreement, according to which, it should be ensured that each vessel sailing under the flag of a contracting country fully complies with the set safety standards.

The aforementioned safety standards concern the structure and design of any merchant vessel, the equipment of the vessel and generally her function (Oliver, 2018; Talley, 2008; World Meteoroogical Organization, 2016).

The first version of the SOLAS Convention was adopted in 1914. The SOLAS 1914 convention was a response to the historic sinking of the Titanic on the 14th of April, 1912 (Kelly, 2013), which led to death more than 1500 people (Oltedal and Lützhöft, 2018). The purpose of the SOLAS 1914 convention was the avoidance of a similar accident (Oliver, 2018). It is worth noting that, 1914 is considered as the year the maritime safety system was born, but, since then, it has evolved a lot (Kopacz et al., 2001).

The second version of the SOLAS international convention was adopted in 1929. Numerous countries of great power were part of the agreement including Australia, Canada, United Kingdom, Japan and the Netherlands. All of the aforementioned countries and, of course, the rest of the participants, were forced to implement the rules and regulations of the convention thoroughly.

Following the tragical on-board fire of "SS Morro Caste" cruise ship (1934) and soon after the Second World War was over, the third version of the SOLAS Convention was adopted in 1948, almost 20 years after the last approved agreement. The countries that agreed with the treaty grew in number. In the 1948 SOLAS convention, numerous rules that had not been clarified before, were regulated. In the aforementioned rules, including others, the rescue equipment, the vessel design and the vessel's official documents were considered. The 1948 SOLAS convention consisted of 6 chapters and it came into force in 1954.

The 17th of June, 1960, was the first time that the SOLAS meeting was convened by the Inter-Governmental Maritime Consultative Organisation (IMCO). The participant countries reached the number of 55. The 1960 SOLAS convention included numerous technical maritime evolvements and updated regulations and it entered into force on the 26th of May, 1965.

In the SOLAS 1974 convention a new system of amendments is introduced, according to which, a specific and rational period of time should pass until every accepted change enters into force. The aforementioned method is analysed in the Article VIII of the convention. It is worth noting that, due to this new system of amendments, the SOLAS 1974 convention is considered to be the last SOLAS treaty and each new, officially agreed amendment is added as a renewal to the convention. This last version of SOLAS came into force on the 25th of May, 1980.

Since 1974, a very large number of amendments has been added to the international maritime treaty. Today, the contracting countries amount to 165, a quantity that corresponds to the 99.04% of the gross tonnage of the world's merchant fleet (International Maritime Organisation, 2020a).

3.4. The MARPOL Convention

In 1967, in England, the grounding of the tanker Torrey Canyon was recorded, together with the resultant spillage of 120,000 tons of crude oil. The aforementioned pollution was, up to then, the highest of all times, affecting not only the British waters, but also reaching the French coastline and the Biscay Bay (MARPOL, 1978; Mattson, 2006). The accident of Torrey Canyon led to the adoption of the International Convention for the Prevention of Pollution from Ships, MARPOL 73/78. The name of the convention indicates the signing year of the treaty (1973), and the year the "1978 Protocol" was adopted. The "1978 Protocol" was related to the 1973 Convention, but it included further additions concerning the construction and operation of tankers, as, the years 1976-1979 numerous casualties involving tankers were reported.

The MARPOL 73/78 convention is another very important shipping tool for the achievement of the maritime safety, and, specifically, the safety of the maritime environment (Kopacz et al., 2001). It consists of six Annexes, each of them considering a specific type of pollution caused by the operation of ships. The six Annexes are listed below:

a. Annex I: Prevention of pollution by oil
b. Annex II: Control of pollution by noxious liquid substances in bulk
c. Annex III: Prevention of pollution by harmful substances carried by sea in packaged form
d. Annex IV: Prevention of pollution by sewage from ships
e. Annex V: Prevention of pollution by garbage from ships
f. Annex VI: Prevention of air pollution from ships

Annex I came into force on the 2nd of October, 1983. Every vessel is obliged to comply with the aforementioned annex. It is considered as one of the most important Annexes, as oil discharge causes significant harm to the marine environment. Indicatively, the grounding casualty of Exxon Valdez is highlighted, which spilled 37,000 tons of oil and led to death thousands of coastal animals, including birds, otters, seals, whales and others (Mattson, 2006; Schmidt-Etkin, 2011; Szepes, 2013).

Annex II of the MARPOL 73/78 convention came into force on the 6th of April, 1987, and the compliance with it is obligatory, too. Regulations for three categories of noxious liquid substances carried in bulk are included in the annex, together with a fourth category, which considers all the other (non-pollutant) bulk substances. The substances that belong to the fourth category do not fall under the characteristics of the other three categories (Harrison, 2017).

The third Annex of MARPOL (Annex III) was enforced on the 1st of July, 1992. The details of the substances that are considered as "pollutant" by Annex III, are described in the International Maritime Dangerous Goods (IMDG) Code. The IMDG Code is included in the Annex (Spyrou, 2017).

Annex IV came into force on the 27th of September, 2003, and, since then it has been revised some times. According to Annex IV, the discharge of sewage into the sea waters is not allowed, unless the distance between the sewage and the nearest coast is such, that the sewage is not considered to harm the maritime environment. This distance is specified in the Annex and is not the same for the different types of vessels or the different marine areas (Jarzemskis and Jarzemskiene, 2016; Spyrou, 2017).

Annex V of MARPOL 73/78 was enforced on the 31st of December, 1988. Generally, the discharge of any kind of garbage is prohibited according to this annex. However, a number of exceptions does exist, which are explained in regulations 4, 5, 6 and 7 of the Annex.

Annex VI on the 19th of May, 2005. The last years, Annex VI is considered to be getting significant importance, although, at the beginning, it had not received wide acceptance. The purpose of this Annex is the regulation of the pollution which is caused to the environment by the ship emissions (NOx, Sox, VOCs, etc).

It is worth noting that, in the Annexes I, II, IV, V and VI of MARPOL 73/78, different "special areas" are determined (see Tables 3.1 and 3.2). A special area is a geographical region, into the frames of which, a higher protection level is considered, due to ecological and oceanographical reasons and to the sea traffic density (Spyrou, 2017).

Table 3.1: Special Areas of Annexes I,II and IV of the MARPOL 73/78 Convention (International Maritime Organisation, 2020b)

Adoption, entry into force & date of taking effect of Special Areas			
Special Areas	**Adopted #**	**Date of Entry into Force**	**In Effect From**
Annex I: Oil			
Mediterranean Sea	2 Nov 1973	2 Oct 1983	2 Oct 1983
Baltic Sea	2 Nov 1973	2 Oct 1983	2 Oct 1983
Black Sea	2 Nov 1973	2 Oct 1983	2 Oct 1983
Red Sea	2 Nov 1973	2 Oct 1983	*
"Gulfs" area	2 Nov 1973	2 Oct 1983	1 Aug 2008
Gulf of Aden	1 Dec 1987	1 Apr 1989	*
Antarctic area	16 Nov 1990	17 Mar 1992	17 Mar 1992
North West European Waters	25 Sept 1997	1 Feb 1999	1 Aug 1999
Oman area of the Arabian Sea	15 Oct 2004	1 Jan 2007	*
Southern South African waters	13 Oct 2006	1 Mar 2008	1 Aug 2008
Annex II: Noxious Liquid Substances			
Antarctic area	30 Oct 1992	1 Jul 1994	1 Jul 1994
Annex IV: Sewage			
Baltic Sea	15 Jul 2011	1 Jan 2013	**

Table 3.2: Special Areas of Annexes V and VI of the MARPOL 73/78 Convention (International Maritime Organisation, 2020b)

Adoption, entry into force & date of taking effect of Special Areas			
Special Areas	**Adopted #**	**Date of Entry into Force**	**In Effect From**
Annex V: Garbage			
Mediterranean Sea	2 Nov 1973	31 Dec 1988	1 May 2009
Baltic Sea	2 Nov 1973	31 Dec 1988	1 Oct 1989
Black Sea	2 Nov 1973	31 Dec 1988	*
Red Sea	2 Nov 1973	31 Dec 1988	*
"Gulfs" area	2 Nov 1973	31 Dec 1988	1 Aug 2008
North Sea	17 Oct 1989	18 Feb 1991	18 Feb 1991
Antarctic area (south of latitude 60 degrees south)	16 Nov 1990	17 Mar 1992	17 Mar 1992
Wider Caribbean region including the Gulf of Mexico and the Caribbean Sea	4 Jul 1991	4 Apr 1993	1 May 2011
Annex VI: Prevention of air pollution by ships (Emission Control Areas)			
Baltic Sea (SO_x) (NO_x)	26 Sept 1997 7 July 2017	19 May 2005 1 Jan 2019	19 May 2006 1 Jan 2021****
North Sea (SO_x) (NO_x)	22 Jul 2005 7 July 2017	22 Nov 2006 1 Jan 2019	22 Nov 2007 1 Jan 2021****
North American ECA (SO_x and PM) (NO_x)	26 Mar 2010	1 Aug 2011	1 Aug 2012 1 Jan 2016***
United States Caribbean Sea ECA (SO_x and PM) (NOx)	26 Jul 2011	1 Jan 2013	1 Jan 2014 1 Jan 2016***

Status of multilateral conventions and instruments in respect of which the International Maritime Organization or its Secretary-General perform depositary or other functions as at 31 December 2002.

* The Special Area requirements for these areas have not yet taken effect because of lack of notifications from MARPOL Parties whose coastlines border the relevant special areas on the existence of adequate reception facilities (regulations 38.6 of MARPOL Annex I and 5(4) of MARPOL Annex V).

** The new special area requirements, which entered into force on 1 January 2013, will only take effect upon receipt of sufficient notifications on the existence of adequate reception facilities from Parties to MARPOL Annex IV whose coastlines border the relevant special area (regulation 13.2 of the revised MARPOL Annex IV, which was adopted by resolution MEPC.200(62) and which entered into force on 1 January 2013).

*** A ship constructed on or after 1 January 2016 and is operating in these emission control areas shall comply with NO_x Tier III standards set forth in regulation 13.5 of MARPOL Annex VI.

**** A ship constructed on or after 1 January 2021 and is operating in these emission control areas shall comply with NO_x Tier III standards set forth in regulation 13.5 of MARPOL Annex VI.

3.5. The STCW Convention

The vessel accident that led to the adoption of the STCW convention is the grounding of the tanker Amoco Cadiz in 1978. The result of the casualty was an oil spillage of 227,000 tons, which infected more than 200 kilometers of the British coast and killed 20,000 birds and other marine and coastal animals (O'Sullivan, 1978; Oltedal and Lützhöft, 2018). The convention was adopted the same year the accident occurred, in 1978, in London, at a conference held by the IMO. It was enforced in 1984. Since the date of adoption, the STCW convention has been revised numerous times (Matsidi, 2014). A complete and clarifying revision of the convention was made in 1995 and since then, it is often called the STCW 78/95 convention.

The purpose of the STCW convention is the establishment of the maritime safety from the perception of life and property. As its name indicates, the STCW convention sets global minimum requirements of training, certification and watchkeeping adequacy for seamen. It applies to every trading vessel, apart from combatant ships, fishing boats or pleasure yachts (Witt, 2007). It was the first official international convention dealing with the concept of human performance responsibility in vessel operations. The study of human factor is very complicated, but, nevertheless, essential. As it has already been highlighted, human error leads to marine casualties at a percentage of 75-96%.

3.6. The Collision Regulations

According to the international literature, collision is one of the most frequent ship accidents (Goerlandt and Kujala, 2011; Huang and van Gelder, 2018; Karahalios, 2014; Li et al., 2012) and as a result, a set of regulations have been implemented, aiming at the minimization of the risk that is linked to this type of casualty. The collision regulatory framework that is in force nowadays is the International Regulations for Preventing Collisions at Sea (COLREGs), adopted in 1972 (International Maritime Organisation, 1972). The COLREGs are a renewal of the Collision Regulations of 1960, but, even before this adoption, numerous informal collision regulations did exist, a short analysis of which is presented below.

3.6.1. The History of the Collision Regulations

In 1840, the London Trinity House composed an amount of safety regulations which came into force in 1846 (Cockcroft and Lameijer, 2003). One of the included regulations was regarding collision avoidance, as it referred to the passing priority of a steam vessel operating in limited waters. In 1858, the British shipping industry made a requisition for vessels to be equipped with fog signals and coloured sidelights.

In 1863, the British Board of Trade published the “Rules to Prevent Collisions at Sea” or else known as the “Articles”. In 1864, these rules had been established to more than thirty countries. On the 29th of April, 1864, President A. Lincoln set into force chapter 69 of the “Rules to Prevent Collisions at Sea”.

In 1867, Thomas Gray composed a brochure of useful naval assistance, which became famous and is still cited in some books. In 1880, the Articles of 1863 were enhanced with rules which were considering the whistle signals. In 1889, regulations for preventing collision at sea were introduced in the International Maritime Conference that was held in Washington. These regulations were enforced by numerous countries, such as the United Kingdom and the America (1897). In 1910, another Maritime Conference was held in Brussels. The adopted rules and regulations were slightly amended then and, up to 1954, they were still in application.

In the SOLAS Conference that was held in 1929, new amendments were proposed but did not ever come into force. However, an informal agreement was made, which was considering the steering and turning commands. This agreement was enforced in 1933. New changes were added in the regulations in the SOLAS Conference of 1948, regarding the lights and the sound signals of the vessels. The aforementioned rules came into force in 1954.

Although some efforts to implement collision regulations had been made, no significant adoption or change was recorded. However, in the SOLAS Conference of 1948 the issue of radar possession was raised, along with the captain’s treatment of the navigational instruments. Thus, this conference set the principles for a major and massive change in the way the collision avoidance was being dealt with.

3.6.2. The Collision Regulations of 1960

The years after the enforcement of the third version of the SOLAS Convention (1948) were very important, as a very large number of vessels was equipped with a radar. However, it was clear that the regulations needed to be renewed. Thus, another International Conference was held by IMCO, in London, 1960, known as the 1960 Conference. During this conference, some proposals were added, basically related on the use of radar. Moreover, the vessel’s reaction in case of restricted visibility was discussed, but this matter was not finally included in the Rules. The result of the 1960 Conference was the 1960 SOLAS Convention and the Collision Regulations of 1960. The Collision Regulations of 1960 entered into force in 1965.

Nowadays, the regulations that are in force are the COLREGs, which are a renewal of the Collision Regulations of 1960.

3.6.3. The COLREGs

The minimisation of human effect on shipping collision accidents has created the need of enactment of collision avoidance rules and regulations (Statheros et al., 2008). The necessary actions that should be taken by the people who work onboard in order to avoid collisions with other ships, are listed in the COLREGs convention (Hilgert and Baldauf, 1997; Statheros et al., 2008). The COLREGs, or else called, “the Rules of the Road”, were adopted in 1972 by IMCO, in the International Conference that was held in London.

The COLREGs entered into force on the 15th of July 1977, but several modifications have occurred since then. The aforementioned convention consists of six (A-F) Parts, forty-one (1-41) Rules and four (I-IV) Annexes. The rules and regulations that are listed in the convention include concerns about the lights of the vessel, her shape and the required sound signals. Also, the vessel’s passing priority, depending on whether she is the “stand-on” or the “give-way” vessel is well defined in the COLREGs (Perera et al., 2010).

The COLREGs refer to all vessels sailing in the international waters and indicate the necessary actions that should be taken in order to evade collision between two or more vessels. The focal point of these regulations is the preservation of an appropriate visual and acoustic view and a safe speed. However, the materialization of the aforementioned navigational characteristics is highly depended on various factors, such as the vessel’s length and her ability to maneuver, the traffic density, the weather conditions, the illumination, the presence or absence of radar equipment etc. Moreover, according to the COLREGs, special attention should be given when a vessel sails in narrow channels or in restricted visibility, or when she overtakes another vessel.

Whenever two sailing vessels approach one another, the one shall avoid the way of the other. The COLREGs present three different situations, according to the vessels’ encounter direction: the head-on, the crossing and the overtaking situation. Overtaking is considered to take place when a vessel’s direction is more than 22.5 degrees abaft the beam of the other vessel. The following figure (Figure 3.1.) is presented in the paper of Xu et al. (Xu et al., 2014) and illustrates the three potential encounter situations of two vessels that are about to collide.

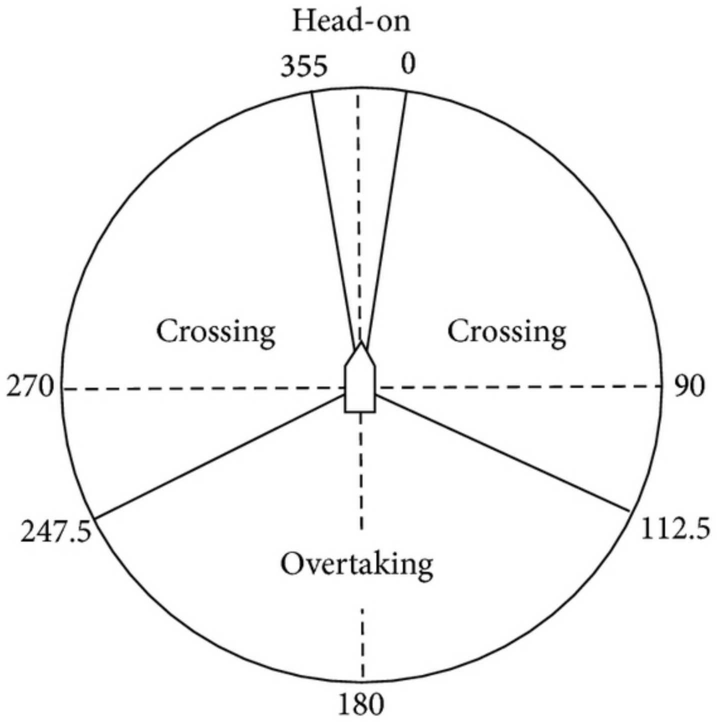


Figure 3.1: Vessel encounter situations

It is worth noting that, the compliance with the rules and regulations of "the Rules of the Road" is of high importance in order to avoid a collision accident. However, numerous serious collisions between vessels have occurred due to the violation of the COLREGs. Indicatively, in the paper of Statheros et al., a percentage of 56% of collision accidents is highlighted, according to which, the cause of the accident was the violation of the COLREGs rules (Statheros et al., 2008).

4. Statistical Data Review

4.1. Introduction

The international trade is served by merchant vessels to a percentage higher than 90% (Allianz Global Corporate and Specialty, 2019a; Katsamaki, 2015). Thus, the avoidance of a shipping casualty is an issue that concerns both the maritime world and the international business world. However, as the statistical analysis reveals, the shipping accidents are unfortunately numerous and happen very often.

A shipping accident is an undesired occurrence that might lead to personal injury or even fatality, property and environmental damage (Ceyhun, 2014). Common shipping accidents are collision, grounding, contact, capsizing or listing, fire or explosion, flooding or foundering. Compared to the other types of shipping accidents, collisions and groundings happen with a higher frequency and might have serious consequences (Pedersen, 2010; Silveira et al., 2013; Zhang et al., 2012). According to the study of Eliopoulou and Papanikolaou (Eliopoulou and Papanikolaou, 2007), althouhg collisions and groundings are the most frequent shipping accidents for aframax tankers, VLCC (Very Large Crude Carriers) and ULCC (Ultra Large Crude Carriers) tankers suffer a structural failure more often. However, the latter two mentioned vessels -and especially the ULCC tankers- are enormously big and do not fall within the usual research scope (Farmakis, 2011; Spyrou, 2017).

Statistical data of shipping accidents are demonstrated in the present paper, in the tables and diagrams that follow (see Table 4.1-4.3, Figures 4.1-4.9). The sources of the statistical data is the TSBC (Transportation Safety Board of Canada, 2018), the UNCTAD (United Nations Conference on Trade and Development, 2019) and the AGCS (Allianz Global Corporate and Specialty, 2019a). Table 4.2 and Table 4.3 illustrate the same statistical data with Figure 4.4 and Figure 4.5, respectively. Figure 4.6 and Figure 4.7 present the average numbers that result from the statistical data that are contained in Tables 4.2 and 4.3, respectively. The time period that was chosen to be studied and indicated is basically the period of the last 10 years (2009-2018).

4.2. The volume of cargo carried by sea Statistical Data

A large number of vessels is employed every year, thus serving the international trade transport needs. The cargo that is carried by ships is separated into three main categories, according to UNCTAD (United Nations Conference on Trade and Development, 2019):

a. Tanker Cargo: Fuel oil, purified oil products, gas and chemicals
b. Main Dry Bulk Cargo: Iron ores, corn and carbon
c. Other Dry Cargoes: Cargoes carried in containers and the rest general cargo

The aforementioned three categories represent the type of cargoes carried by sea. In Table 4.1 and Figure 4.1 the cargo amount (in million tons) that belongs to each category globally, together with the corresponding percentages are presented. According to Table 1, the total international trade is mainly represented by dry cargo. The sample highlights a year by year increase of the total amount (in million tons) of cargo. In 2010, the highest increase was recorded, namely, 550 million tons, which corresponds to a percentage increase of 7%.

Almost one third of the global trade is carried in tankers. 2009 was the only year that the volume of cargoes carried in tankers reached the percentage of 34% of the world's total volume of trade. Since then, a slight decrease has been reported to this percentage and the last years it has been almost stabilised to 29%. Figure 4.2 indicates the average percentages and volume of the total tanker cargo and the total dry cargo that is carried by sea over the last ten years. According to figure 4.3, the main dry bulk cargoes represent 41% of the total dry cargo. The aforementioned percentage is the average number that has derived from the last ten years (2009-2018).

Table 4.1: International Trade Volumes and Percentages

	International Trade [x10^{6} tons]										
Year	Tanker Cargo		Main Bulks		Other Dry Cargo		Total Dry Cargo		Total	Increase	
										x10^{6} tons	%
2018	3194	29%	3210	29%	4601	42%	7811	71%	11005	289	3%
2017	3146	29%	3151	29%	4419	41%	7570	71%	10716	421	4%
2016	3058	30%	3009	29%	4228	41%	7237	70%	10295	272	3%
2015	2932	29%	2930	29%	4161	42%	7091	71%	10023	180	2%
2014	2825	29%	2964	30%	4054	41%	7018	71%	9843	330	3%
2013	2828	30%	2734	29%	3951	42%	6685	70%	9513	318	3%
2012	2840	31%	2564	28%	3791	41%	6355	69%	9195	420	5%
2011	2785	32%	2364	27%	3626	41%	5990	68%	8775	368	4%
2010	2752	33%	2232	27%	3423	41%	5655	67%	8407	550	7%
2009	2641	34%	1998	25%	3218	41%	5216	66%	7857	-	-

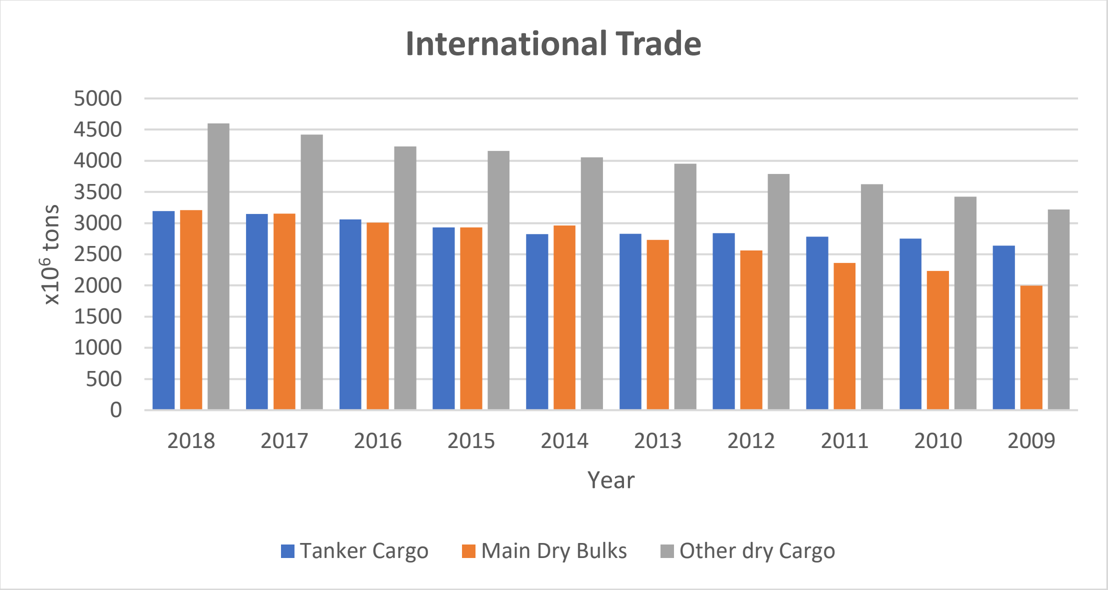


Figure 4.1: Cargoes (in million tons) carried by sea over the past ten years (United Nations Conference on Trade and Development, 2019)

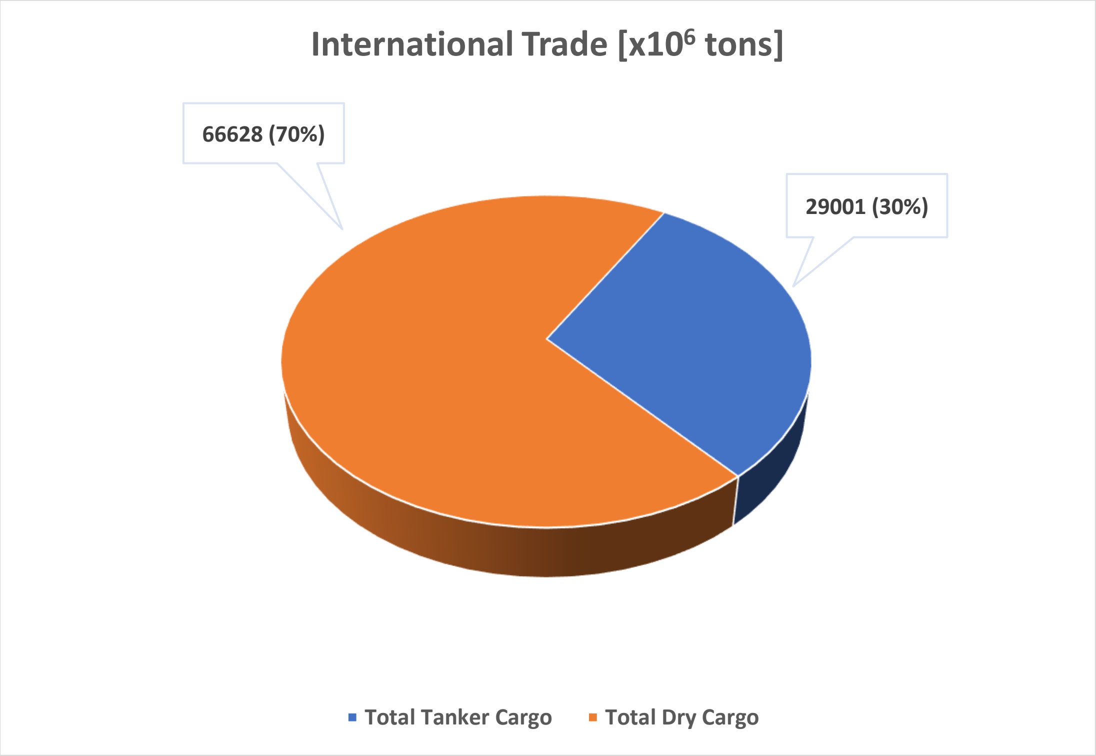


Figure 4.2: The volumes and percentages of tanker cargo and dry cargo, average 2009-2018

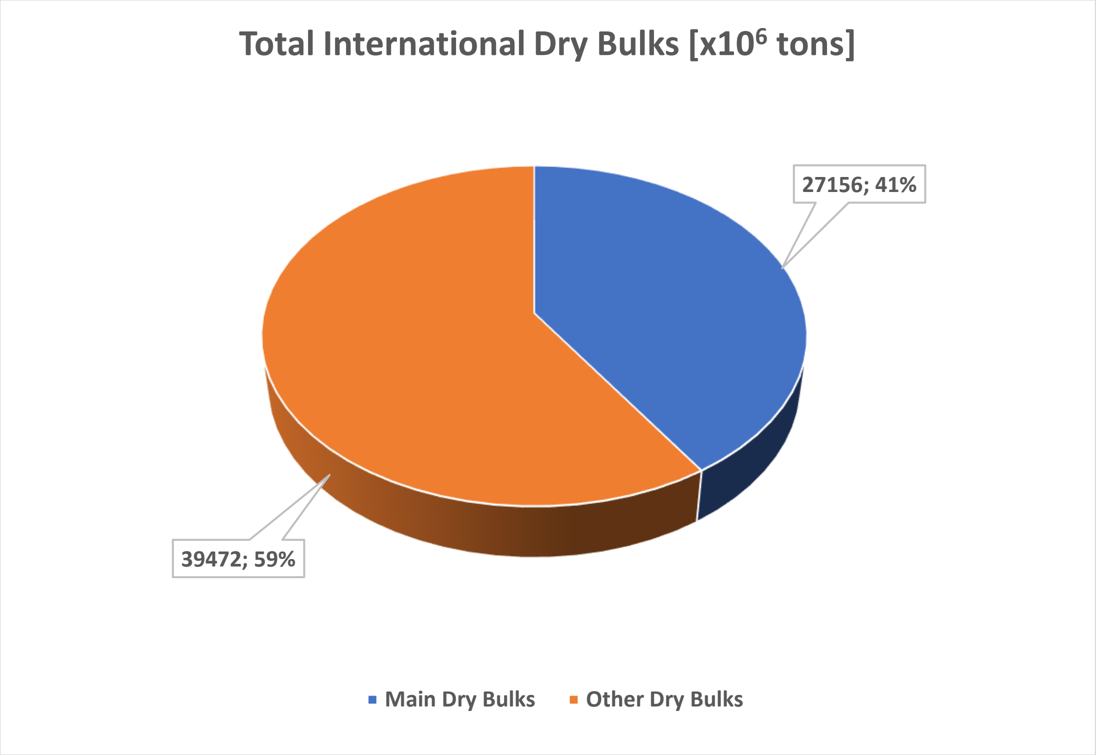


Figure 4.3: The volumes and percentages of dry bulks, average 2009-2018

4.3. Type of Shipping Accidents Statistical Data

According to the statistical data that are demonstrated in Table 4.2 and Figure 4.4, in most of the examined years, collision was the most frequent type of shipping accidents. However, grounding casualty had the highest happening percentage the years 2009, 2010 and 2015. Fire/ explosion percentages varied between the values 12-20%. During 2011, 53 accidents of fire/explosion happened, a number that corresponds to the highest happening percentage for the specific category, namely, 20%. The other types of shipping accidents have, in average, happening percentages, less than 7%. Shipping accidents that are not suited to a casualty category occur with an average happening percentage of 13%. It is worth saying that, 2009 and 2010 were the years that the shipping accidents were the most, in total, while, in 2012 and 2015, the least total number of casualties at sea were reported. More specifically, 301 shipping accidents in total occurred in 2009 and 273 in 2010, while, in 2012 and 2015, the shipping casualties were 216 and 213, respectively.

4.4. Type of Vessels involved in Shipping Accidents Statistical Data

Shipping accidents occur between barges, cargo vessels that carry either solid or liquid cargo, ferry boats, fishing boats, passenger ships, service ships, tugs and others.

According to Table 4.3, the vessel type that is involved in collision casualties more often, is the fishing vessel. However, the number of fishing boats might be remarkably higher that the number of other types of vessels, and thus the results might be justifiable (Norwegian Maritime Directorate, 2011).

According to the statistical data that are illustrated in Table 4.3, passenger and liquid cargo vessels have the lowest accident participation percentages, meaning that, less than 5% in average of such ships are involved in shipping accidents. As it has been already referred, fishing boats are the most frequent participants in shipping casualties, with percentages that exceed the value of 28%. However, shipping accidents in which solid cargo vessels are involved have also high happening percentages. Notably, in 2014, 68 solid cargo ships participated in a casualty and, in 2012, 63. Thus, the participation percentage of solid cargo ships was 24% in 2014 and 26% in 2012. These two percentages have been the highest for the specific vessel category. Barges, ferry boats, service ships, tugs and others are involved in shipping accidents with percentages that vary from 6-11% in average. It is worth mentioning that the highest total number of involved vessels in an accident was in 2009, when 337 ships suffered shipping casualties.

Table 4.2: Type of Shipping Accidents Statistical Data over the past ten years (Transportation Safety Board of Canada, 2018)

	Type of Shipping Accidents												
Year	Collision		Grounding		Fire/Explosion		Capsizing		Foundering		Others		Total (100%)
2018	82	**35%**	58	25%	35	15%	10	4%	27	12%	21	9%	233
2017	89	**38%**	52	22%	33	14%	5	2%	22	9%	32	14%	233
2016	89	**34%**	65	25%	44	17%	7	3%	26	10%	33	13%	264
2015	57	27%	59	**28%**	33	15%	10	5%	16	8%	38	18%	213
2014	88	**35%**	61	24%	29	12%	3	1%	26	10%	42	17%	249
2013	79	**33%**	62	26%	31	13%	8	3%	14	6%	44	18%	238
2012	78	**36%**	69	32%	34	16%	6	3%	10	5%	19	9%	216
2011	87	**34%**	73	29%	50	20%	2	1%	10	4%	32	13%	254
2010	64	23%	102	**37%**	53	19%	8	3%	20	7%	26	10%	273
2009	81	27%	110	**37%**	50	17%	9	3%	20	7%	31	10%	301

Table 4.3: Type of Vessels involved in Shipping Accidents Statistical Data over the past ten years (Transportation Safety Board of Canada, 2018)

	Type of Vessels involved in Shipping Accidents																		
Year	Barge		Liquid Cargo		Solid Cargo		Ferry		Fishing		Passenger		Service Ship		Tug		Others		Total (100%)
2018	29	11%	9	3%	47	18%	10	4%	76	28%	14	5%	27	10%	25	9%	31	12%	268
2017	20	7%	10	4%	39	15%	12	4%	88	33%	15	6%	38	14%	25	9%	21	8%	268
2016	24	8%	7	2%	40	13%	19	6%	91	29%	16	5%	50	16%	26	8%	37	12%	310
2015	10	4%	12	5%	37	15%	18	8%	81	34%	17	7%	29	12%	19	8%	17	7%	240
2014	12	4%	14	5%	68	24%	20	7%	92	33%	13	5%	21	7%	22	8%	19	7%	281
2013	19	7%	7	3%	60	22%	13	5%	88	32%	15	5%	36	13%	26	9%	12	4%	276
2012	6	2%	6	2%	63	26%	18	7%	82	34%	15	6%	20	8%	26	11%	5	2%	241
2011	20	7%	10	3%	57	19%	23	8%	99	34%	16	5%	25	9%	24	8%	20	7%	294
2010	17	6%	12	4%	61	21%	19	6%	111	38%	14	5%	29	10%	19	6%	14	5%	296
2009	28	8%	11	3%	63	19%	26	8%	117	35%	17	5%	38	11%	19	6%	18	5%	337

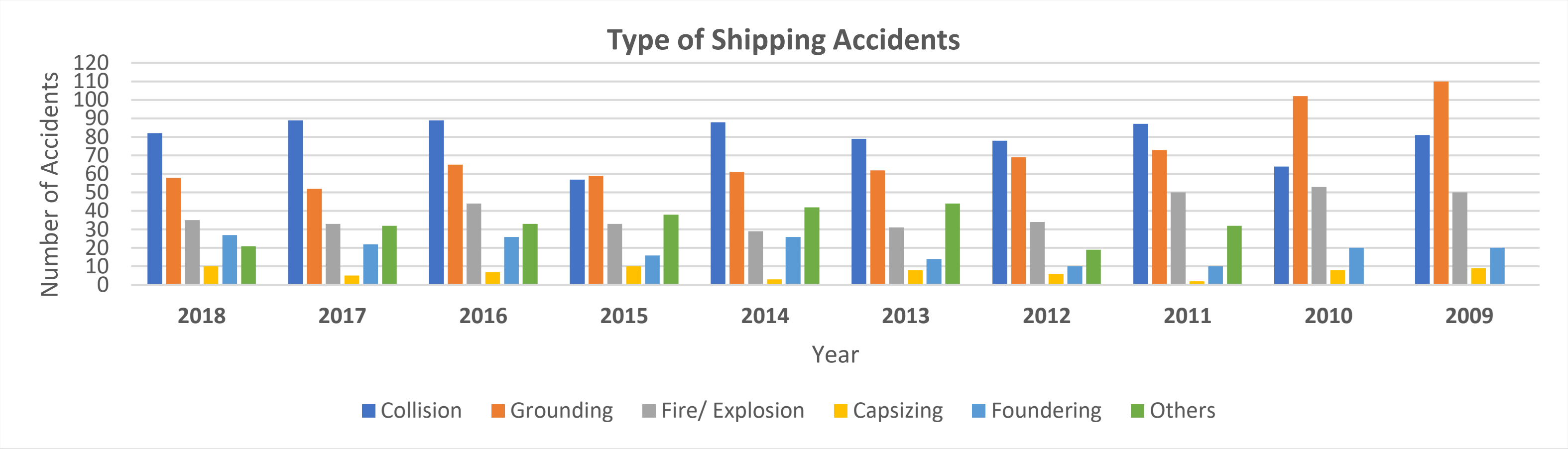


Figure 4.4: Number of Shipping Accidents by Type over the past ten years (2009-2018)

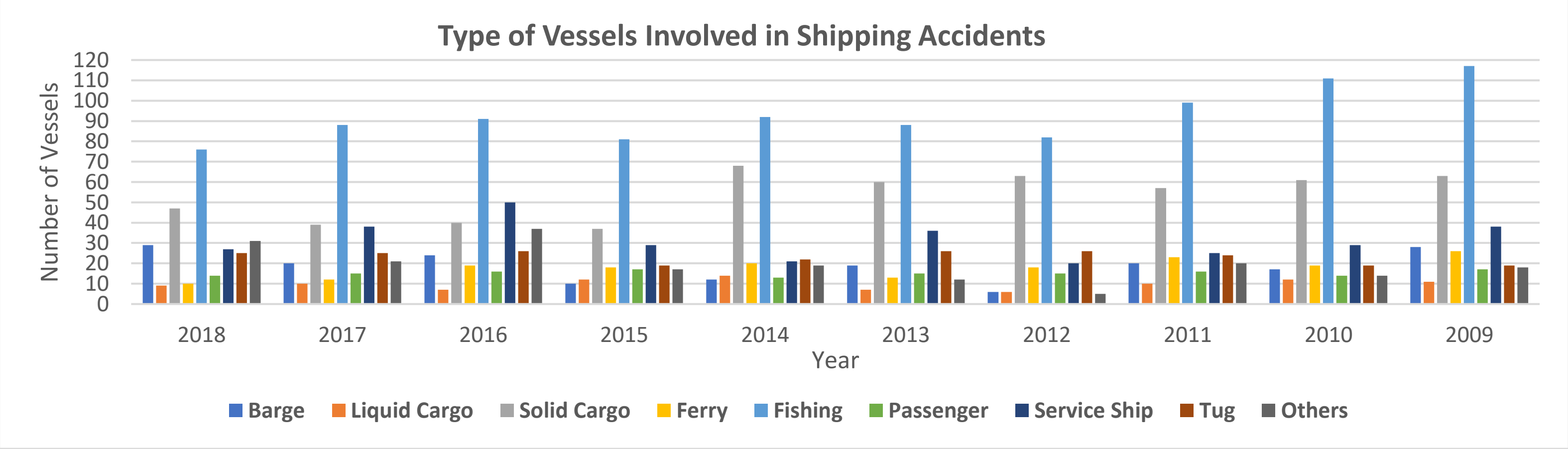


Figure 4.5: Number of Vessels involved in Shipping Accidents by Type over the past ten years (2009-2018)

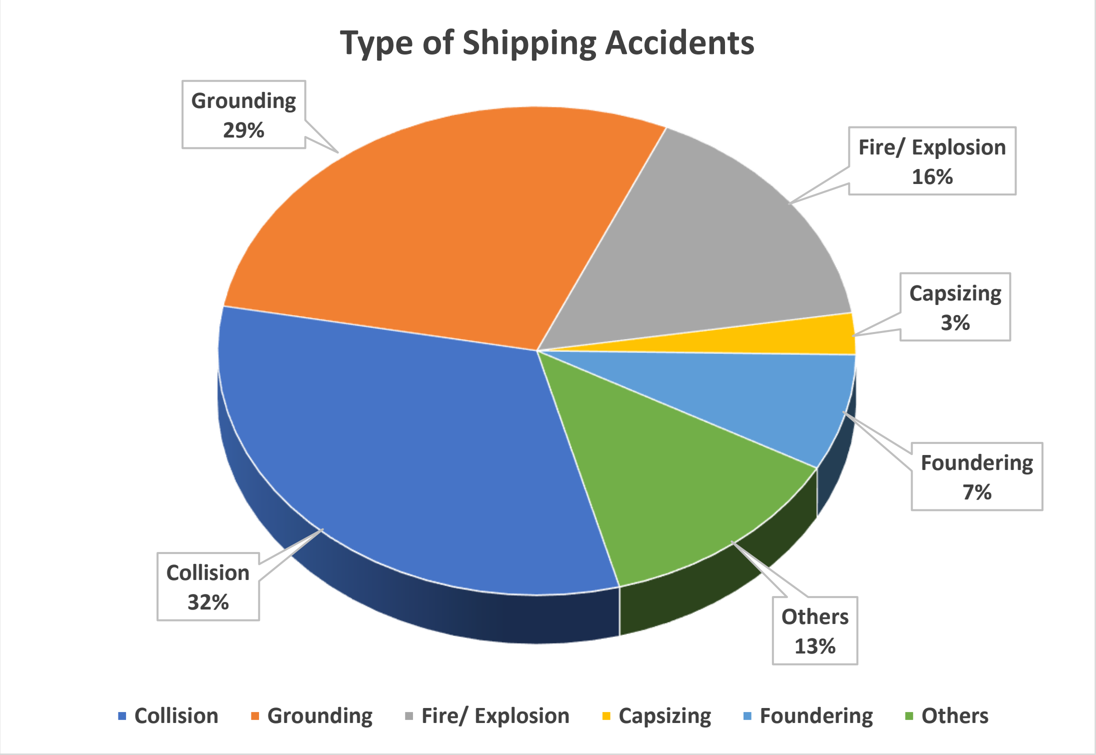


Figure 4.6: Type of Shipping Accidents, average 2009-2018

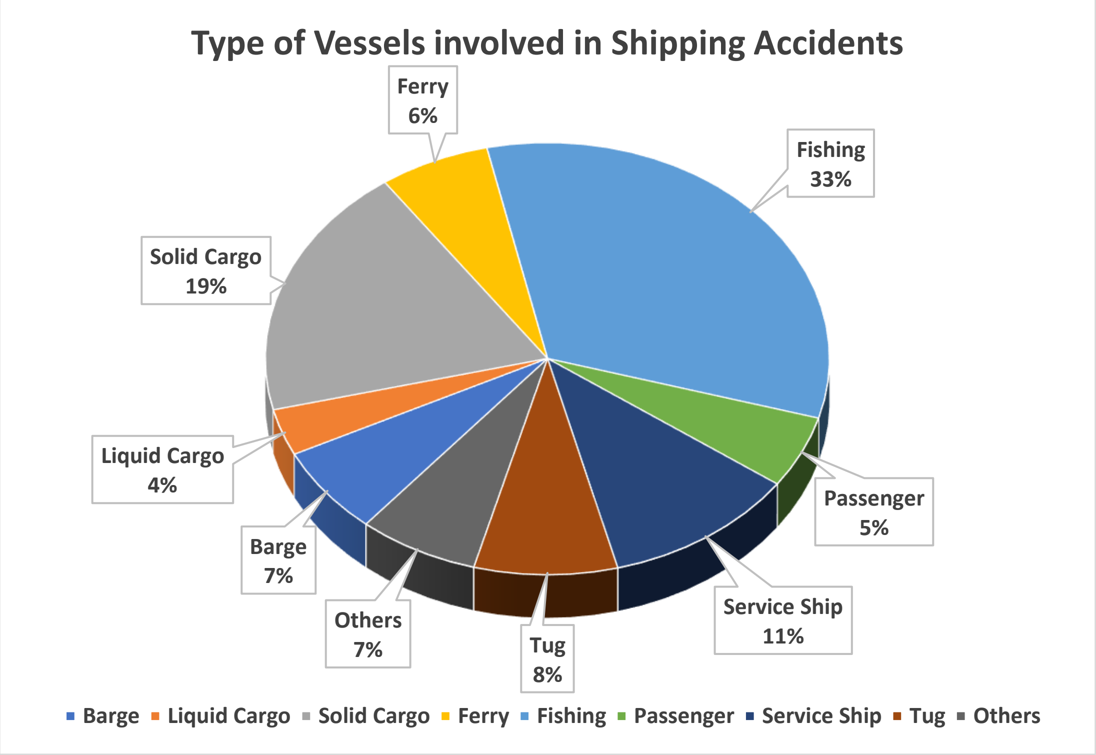


Figure 4.7: Type of Vessels involved in Shipping Accidents, average 2009-2018

4.5. Vessel Total Losses Statistical Data

4.5.1. Number of Recorded Total Losses over the last 10 years

As it is highlighted above, the volume of trade which is carried by sea yearly is very large and corresponds to 90% of the total international volume of trade. However, the shipping accidents which occur every year and the involved vessels are numerous. Some of the vessels which suffer a shipping accident are even led to a total loss.

In Figure 4.8, the number of vessels that suffer a total loss globally is presented. The sample refers to the period of the last 10 years (2009-2018) and vessels of 100 GT and over are only concerned (Allianz Global Corporate and Specialty, 2019a). According to Figure 4.8, in 2018, the number of the total losses was the lowest recorded over the last 10 years. However, this number might get a little bit bigger in the coming years, as, studies on actual losses sometimes lead to a considered total loss, even after the end of the studied year. The mean potential increase over the last nine years is less than 2 total losses annually. In 2009, 2010 and 2012 the recorded total losses were 132, 129 and 127, respectively, and these were the three highest numbers of annual total losses over the last 10 years. It is worth noting that, in 2018, the amount of total losses is 65% decreased, compared to the corresponding 2009 number.

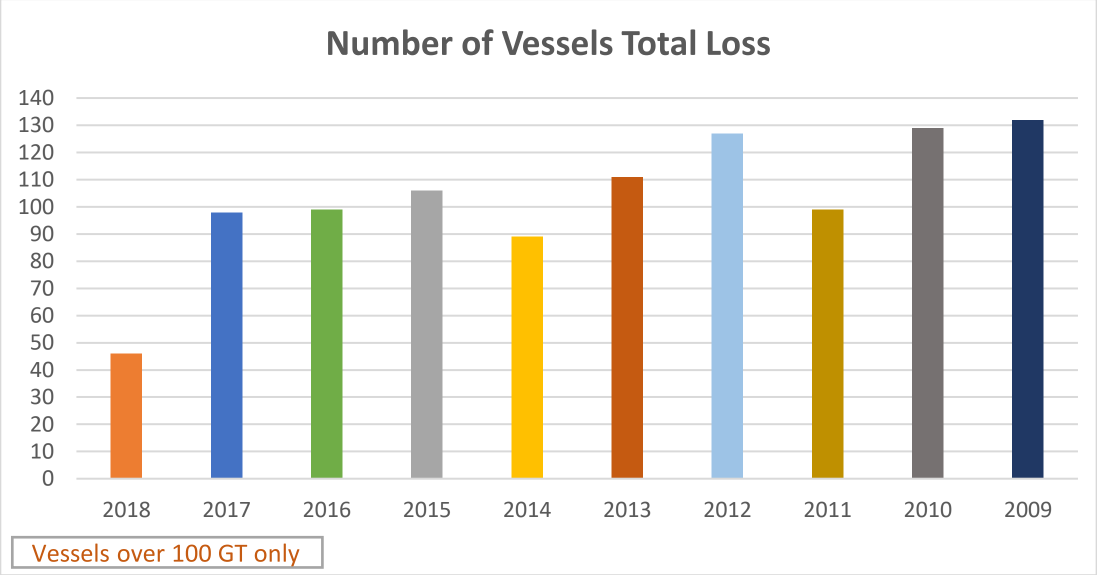


Figure 4.8: Number of recorded total losses, 2009-2018 (Allianz Global Corporate and Specialty, 2019a)

4.5.2. Geographical Area of Recorded Total Losses

The vessel accidents of the last decade have occurred into different geographical areas. According to the statistical data that are presented in AGCS (Allianz Global

Corporate and Specialty, 2019a), most of the accidents that led to a vessel total loss happened in the geographical area which includes South China, Indochina and Philippines (23%). The aforementioned study concerns total losses of ships of 100 GT and over which were recorded over the last decade. The studied regions are located in the European, Asian and African waters. The geographical areas that are not included in the aforementioned three regions, are considered as "All other regions". Statistical data about "All other regions" are considered as well and the recorded total losses there reach a percentage of 22%. Figure 4.9 presents the percentage results of the studied geographical areas.

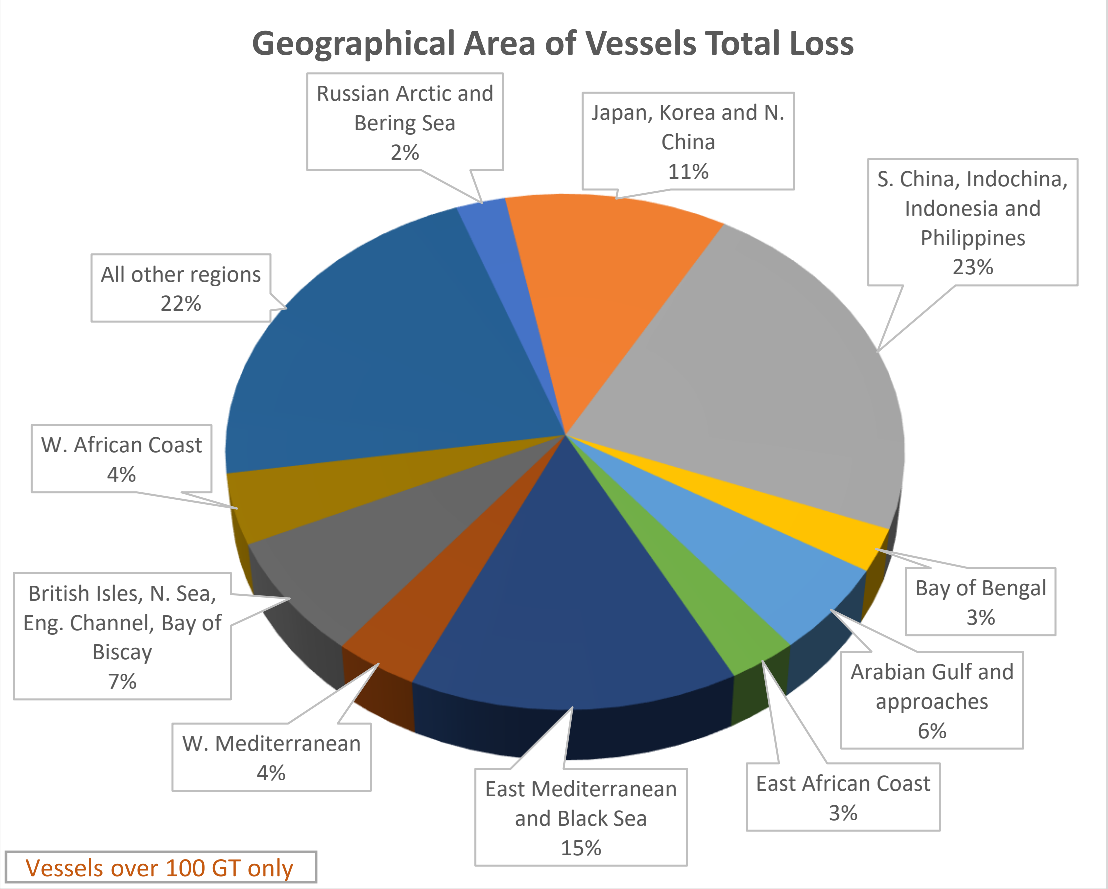


Figure 4.9: Geographical Areas percentages of recorded total losses, average 2009-2018.

4.6. Human Factor Contribution in Shipping Accidents Statistical Data

Research process has revealed that the human factor is closely connected with shipping accidents, as the highest causal percentages of shipping casualties are ascribed to humans. Human errors might result in significant shipping casualties, but, apart from this, they also cause serious financial damages.

It is argued that, 75-96% of shipping accidents (He et al., 2017; Hetherington et al., 2006; Islam and Yu, 2018; Kiosses, 2015; Matsidi, 2014; Perera et al., 2010; Rothblum,

2000) are, up to a certain extent, a result of human error. More specifically, 84-88% of tanker accidents, 79% of towing vessel accidents, 89-96% of collisions, 75% of allisions and 75% of fires/explosions happen due to human error. The aforementioned analytical percentages are presented in Table 4.4 and in Figure 4.10. In the work of Faturachman et al. (Faturachman et al., 2014) human factor contribution to accidents that happen in rivers, seas or lagoons, is accounted as a percentage of 65%. In the same research, natural factor is considered as 24% and others factor as 11%. The referred percentages are illustrated in Figure 4.11. Another study has highlighted human factor as the leading causal factor to 60% of total shipping casualties, while the organisational and management factors receive a percentage of 15% and the other 25% are assigned to technical difficulties (Vagias, 2010).

Table 4.4: Human factor contribution percentages to different accident types (Rothblum, 2000)

Accident Type	Human factor contribution (%)
Accident of Tanker	84-88
Grounding of Towing Vessel	79
Collision	89-96
Allision	75
Fire/Explosion	75

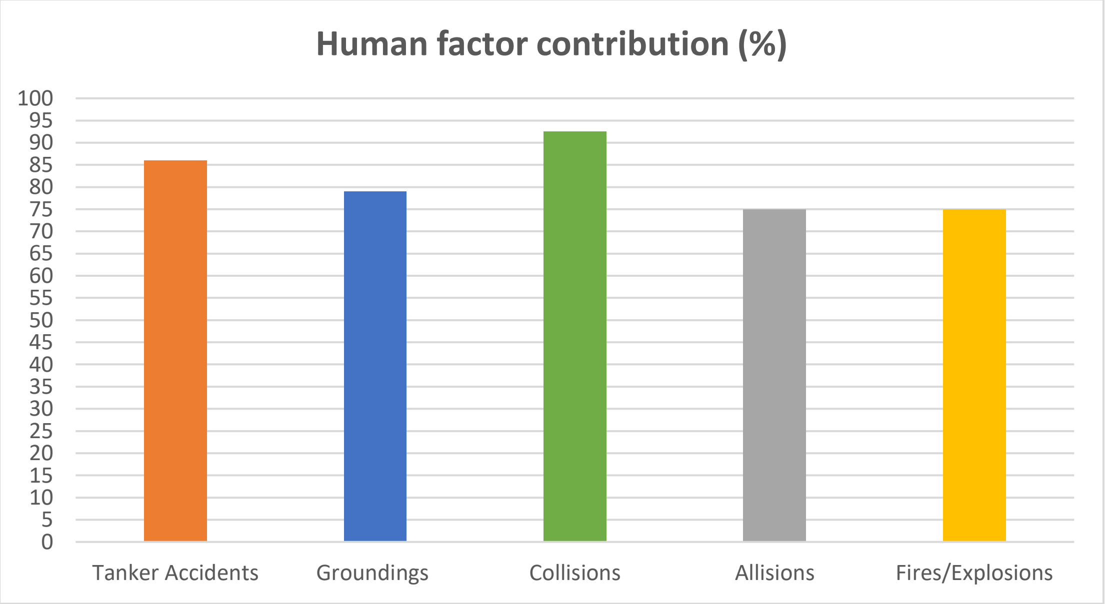


Figure 4.10: Human factor contribution percentages to different accident types (Rothblum, 2000)

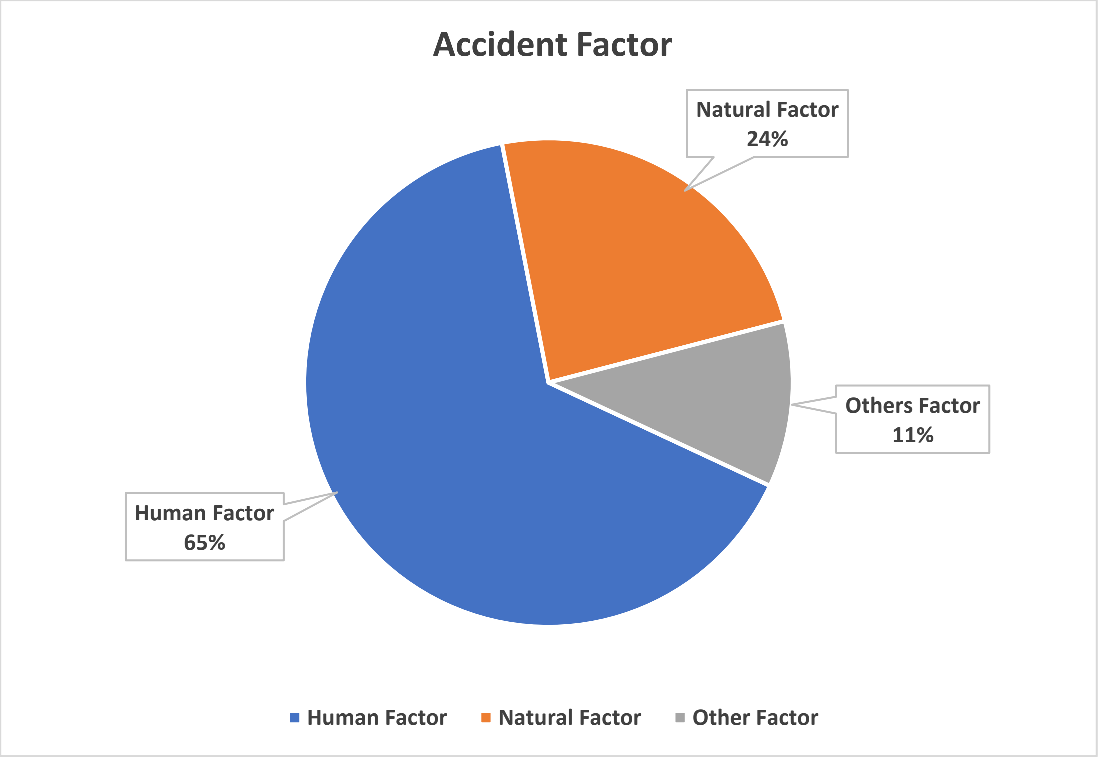


Figure 4.11: Percentages of accident factor (Faturachman et al., 2014)

In the paper of Katsamaki (Katsamaki, 2015), the human factor is considered to cause 70-90% of the marine accidents. The other factors that contribute to such accidents, the age and design of the vessel, lack of unified standards, operating standards-mechanical failures, external factors and other, unknown reasons, are listed in Table 4.5 and Figure 4.12 below. Officers of the watch are said to conduce to groundings and vessel collisions 60%, according to Bebeteidoh and Poku. In fact, their contribution to collision casualties might be even higher (Bebeteidoh and Poku, 2016).

Table 4.5: Percentages of different factors that contribute to marine accidents (Katsamaki, 2015)

Factor	Contribution Percentage (%)
Human Factor	70-90
Age & Design of the Vessel	8-15
Lack of Unified Standards	6-10
Operating Standards-Mechanical Failures	4-7
External Factors	2-5
Unknown Reason	2-5

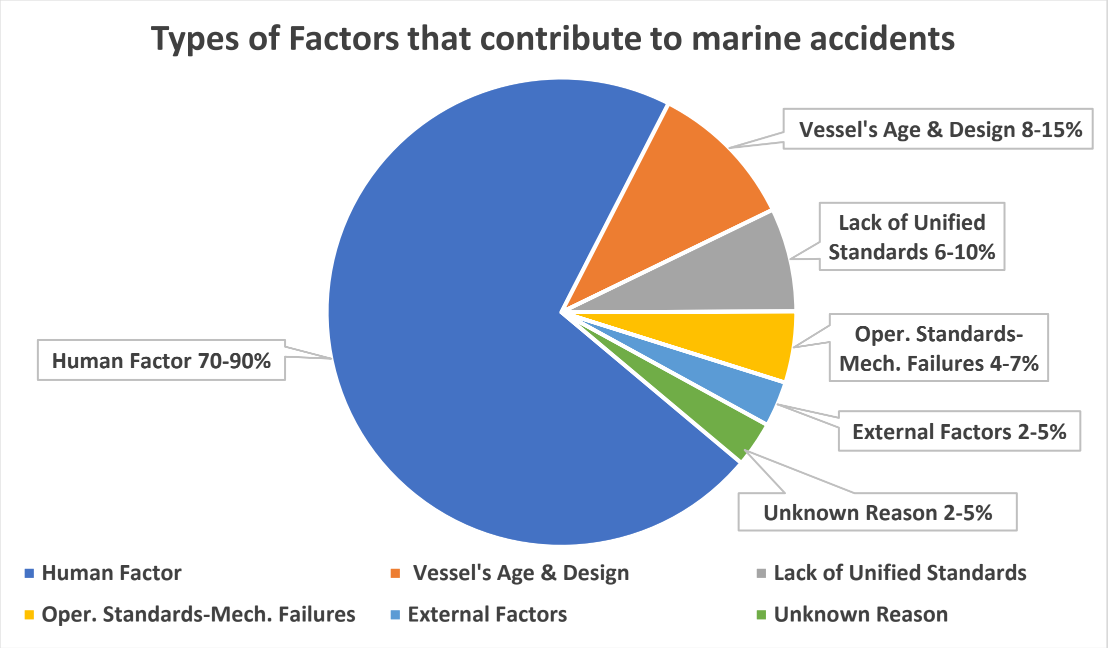


Figure 4.12: Percentages of different factors that contribute to marine accidents (Katsamaki, 2015)

The study of human error impact to shipping accidents has also revealed percentages for specific human factors contribution to the shipping casualties. More analytically, the factor of fatigue is accused for 23% maritime accidents causation, according to Hetherington et al. and Raby and McCallum (Hetherington et al., 2006; Raby and McCallum, 1997). The working load of seamen seems to be one of the most exhausting. In particular, it has been recognised that, during a month, the resting hours of shipmates are the second fewest after people working in the railway (Matsidi, 2014). Apart from fatigue, at a percentage of 80%, mariners declare to suffer from circumstantial or constant working stress, which undermines the levels of their efficiency (Hetherington et al., 2006).

The insufficiency of general knowledge over technical issues also creates serious problems and it is a major factor which contributes to maritime accidents up to 35% (Rothblum, 2000). The appropriate use of radar is one of the most important technical knowledge that should be acquired. However, it is revealed that an unsuitable or deficient use of radar has been made in 73% of collisions that have been studied (Marine Accident Investigation Branch, 2004).

Another factor, connected with human errors, that is able to conduce to shipping accidents is the communication problem between the people working onboard. Indicatively, in a NTSB report it is stated that 70% of serious vessel collisions or allisions happened while a governmental pilot was managing at least one of the involved vessels (National Transportation Safety Board, 1981). Apart from the communication problems, however, OOW total unawareness of the forthcoming vessel is reported to lead to collision accidents at a percentage of 19% (Chauvin et al., 2013). The study that

Grech et al. conducted (Grech et al., 2002), revealed that, 71% of human mistakes which were made in maritime accidents, were due to situation unawareness.

Research process has highlighted that organizational factors contribute to the realization of vessel collision casualties up to 47%. More specifically, the aforementioned percentage represents problems that concern the Safety Management System (SMS) of a company or a lack of success in the conduct of aboard inspections (Chauvin et al., 2013).

5. Consequences of collision accidents

5.1. Introduction

The type of shipping accident which is studied in the present thesis is the vessel collision. Collision between two vessels is assumed to happen, when two ships experience a forcible contact, which leads to a detrimental accident (Kaushik, 2019; Samuelides et al., 2009). The outcome of a vessel collision, as of any shipping accident, might be personal injury or even fatality, property and environmental damage. For the sake of completeness, information about actual ship collisions of the 20th and the 21st century, which resulted in the aforementioned three categories of consequences, are quoted below.

5.2. Collision accidents resulting in fatalities

Loss of life is a terrible result of vessel collision. The fact of fatalities causes great damage to the society and, more than this, it is accused for the defamation of the vessel and the company of the vessel (Lützen, 2001). The risk of fatalities is higher when a passenger ship is involved in a collision and generally in a shipping accident (Samuelides et al., 2007).

During the 20th century, remarkable fatalities have been noted as a collision outcome. Early in the morning of the 29th of May, 1914, the passenger liner "Empress of Ireland" attempted to pass the Norwegian cargo ship "Storstad" but, due to thick fog, a collision was reported between the two vessels and 1012 people lost their lives (Mechem, 2009). A tremendous collision occurred on 27 January, 1949, between the Chinese steamer "Taiping" and a small cargo vessel. "Taiping" was carrying passengers almost twice her capacity and the accident deprived the lives of more than 1500 human beings (Letu, 2011). The bulk carrier "Pyotr Vasyov" collided with the passenger liner *"Admiral Nakhimov"* on the 31st of August, 1986, and 425 fatalities were reported (Song et al., 2010). The oil tanker "Victor" was involved in a collision with the Philippine ferry "Doña Paz" on December 20, 1987, resulting in the death of 4386 people, while the collision between the oil tanker "Agip Abbruzzo" and the Italian ferry "Moby Prince" on the 10th of April, 1991, issued 141 losses of life (Burgherr and Hirschberg, 2008).

Serious collision casualties were observed in the 21st century as well. On the 13th of May, 2012, a collision happened between the ferry "Shariatpur-1" and a cargo vessel. The accident resulted in 114 fatalities (Rashid and Islam, 2017). In October of the same year the ferry "Sea Smooth" and the passenger ship "Lamma IV" collided and 39 people were dead, while 92 were injured. The number of deaths recorded during this casualty was the highest in Hong Kong since 1971 (Yip et al., 2015). On the 16th of

August, 2013, another notable collision occurred, between the passenger vessel “St. Thomas Aquinas” and the cargo ship “Sulpicio Express Siete”. The collision happened in the Mactan Channel, Philippines, and almost 110 fatalities were reported (Katsamaki, 2015). In August of 2017 the “US Navy destroyer John McCain” collided with the oil tanker “Alnic MC”. 10 seamen of the first vessel were driven to death and 48 were hurt, while, on the second vessel, no wounded people were stated (National Transportation Safety Board, 2017).

5.3. Collision accidents resulting in environmental pollution

By using the term environmental outcomes of collision accidents, it is meant the catastrophic effects that oil leakage might have on business connected with angling or tourism, shores or ports, coastal beings and districts, society and, generally, on the financial system (Lützen, 2001). Vessel collisions have led to environmental pollution numerous times.

The oil tankers “Atlantic Empress” and “Aegean Captain”, both under Greek ownership, collided on the 19th of July, 1979, and 286389 tons of oil were spilled into the waters of the Caribbean (Catalano, 2011; Schmidt-Etkin, 2011). Another collision was reported in the Persian Gulf in February of 1983. A tanker and a platform were involved in the accident and the result was an oil spillage of 1500 barrels/day (Catalano, 2011). “Sanchi” ship, carrying crude oil, collided with the cargo vessel “CF Crystal” within the waters of the East China, in January 2018. Eight days after the collision, the tanker sank and almost 1900 tons of fuel oil were spilled (Yin et al., 2018). The Mediterranean was polluted very recently, when, in October 2018, the Tunisian Ro-Ro “Ulysse” collided with the Cypriot container “CSL Virginia”, causing the formation of 7 separate oil spills at a distance of approximately 25 km (Carpenter and Kostianoy, 2018) at the area of the Corsica. Two images of the latter mentioned collision are cited below.

Figure 5.1: The collision between the Tunisian Ro-Ro “Ulysse” and the Cypriot container “CSL Virginia” (Allianz Global Corporate and Specialty, 2019b)

Figure 5.2: The collision between the Tunisian Ro-Ro “Ulysse” and the Cypriot container “CSL Virginia” (gCaptain, 2018)

5.4. Collision accidents resulting in Damage to Property

When two or more vessels collide, each of the vessels might have significant failures and sometimes capsizing and the induced ship loss are an issue. Of course, there are collisions accidents that result in less serious vessel damages (Lützen, 2001; Norwegian Maritime Directorate, 2011).

The outcome of some collisions is the remnants of a shipwreck. The passenger liner “Empress of Ireland” sank after its collision with the Norwegian cargo ship ”Storstad” in 1914 (Mechem, 2009). Sinking was also the fate of both the Chinese steamer “Taiping” in 1949 (Letu, 2011) and the passenger liner “Admiral Nakhimov” in 1986 (Song et al., 2010). The collision that was reported in 1987 between the Philippine ferry “Doña Paz” and the oil tanker “Victor” was followed by a tragic fire onboard the vessels, which, apart from the caused fatalities, led both vessels to the bottom of the sea (Dragan and Isaic-Maniu, 2014). The ferry “Shariatpur-1” was involved in a collision in 2012, which happened in Bangladesh, in the Meghna River. The vessel capsized and afterwards sank (Rashid and Islam, 2017). The passenger ship “Lamma IV” collided with the ferry “Sea Smooth” the same year and suffered numerous construction damages, as she was breached both in her engine room (E/R) and in her Tank room. A large water intrusion resulted in the sinking of the vessel (Lunn and Tang, 2013). The 40 years old passenger vessel “St. Thomas Aquinas” also sank in 2013 after colliding with the cargo ship “Sulpicio Express Siete” (Katsamaki, 2015). The latter mentioned cargo ship was not sank. Pictures from the cargo ship after the collision casualty are presented below.

Sometimes, structural or hull damage of the vessel is the result of the collision accident, without her sinking. On March, 2010, “Hundvåkøy” fishing boat suffered a collision with the cargo vessel ”Hordafor 4”, which was reported between the Norwegian straits (Berg et al., 2011). The accident resulted in the penetration of large amount of sea water into the E/R of the fishing boat, but, hopefully, no crew member was injured (Norwegian Maritime Directorate, 2011). The hull of the warship “US Navy destroyer John McCain” was deformed after her collision with the oil tanker “Alnic MC” in 2017. Not only the external structure of the ship was affected, but the vessel also suffered numerous inner damages. The repairing cost was high. The “Alnic MC” oil tanker had a bulbous damage in her forepeak tank (National Transportation Safety Board, 2017). Pictures from the accident are presented below.

Figure 5.3: The “Alnic MC” oil tanker after the collision casualty (National Transportation Safety Board, 2017)

Figure 5.4: The cargo ship “Sulpicio Express Siete” after the collision (Radio Free Europe/Radio Liberty, 2013)

6. Model Description

6.1. Introduction

In order to study ship collision accidents and the human element contribution to them, the calculation of the vessel collision probability is essential and, more than this, the mentioned probability should be focused on the human factor. The person who is the master’s deputy and who is chiefly in charge of the vessel’s secure passage from a port to another, according to the STCW convention, is the OOW (Deligiannis, 2017). Thus, the whole set up of the model is based on the role and actions of the OOW when the ship is on a collision course.

As it has been already mentioned, the vessel collision accident is being studied through the construction of a PN model. It is worth mentioning that, the type of PN that is developed is a simple (original) PN. The choice of a simple PN development is made, due to the fact that, in the context of the present thesis, the desired model is a static analysis model. More than this, PNs have not been widely used before, in scientific studies that concern the shipping field. Thus, the present analysis has the purpose of remaining understandable and simple. Therefore, the inclusion of the time factor was not considered helpful, at this stage. The developed PN model is an illustration of the series of events that happen before the occurrence of the collision accident. The next and final step is the probability calculation, which is made according to the probability calculation that is presented in the work of Philippi et al. (Philippi et al., 2006).

6.2. Model analysis

The developed model is built in accordance with the logic of the high-level model that is presented in the paper of Sotiralis et al. (Sotiralis et al., 2016) (see Figure 6.1 below). The presented model is enriched with details, the majority of which also appear in the research of Sotiralis et al. and specifically in the BN that is studied in the aforementioned research. However, there are some parts of the model which are slightly differentiated. The details that appear in the model are about the duties of the OOW and the factors that affect the collision avoidance process. The analysis is centered around the reaction of the OOW, but, as more elements affect the collision avoidance ability, other factors, independent from the OOW, are included as well. The vessel's operation is considered to be normal, which means that the potential assessment and action undertaking are able to happen within regular time limits. In the developed model, the other vessel, which is on a collision course, too, is not considered to be able to change the fate of the collision accident. The assessment of the collision is focused on the actions of our OOW. It is assumed that the OOW of the other vessel follows a similar acting procedure and this is the reason why, at the final stage of collision avoidance judgement, the reaction of the other vessel is included.

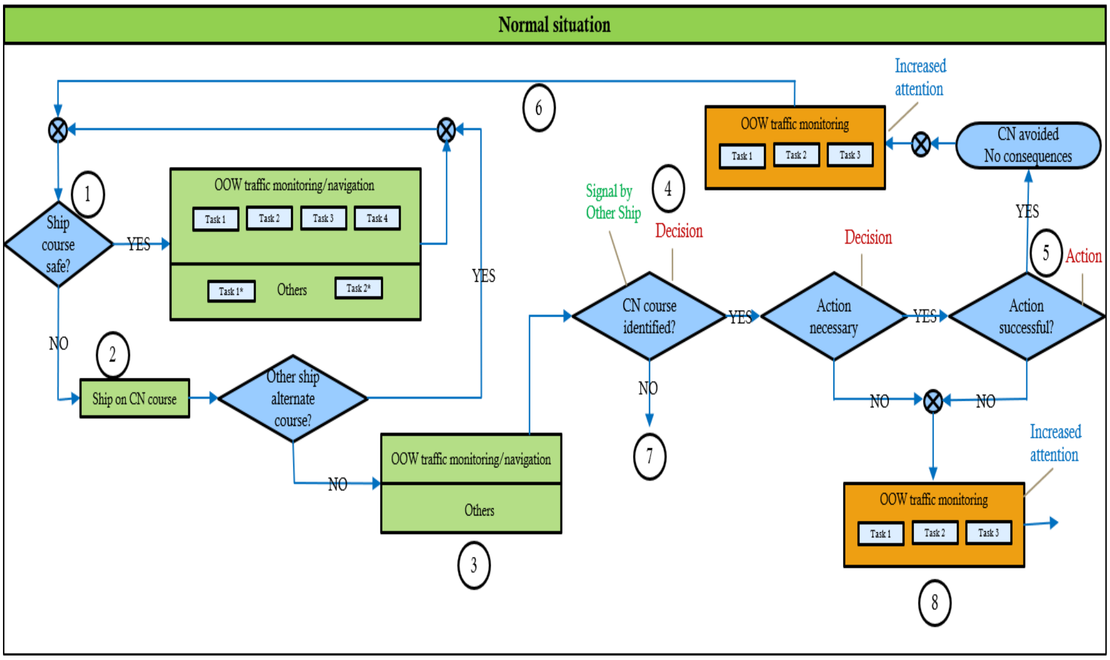


Figure 6.1: The high-level model presenting the regular vessel operation (Sotiralis et al., 2016)

The built model is fully presented below. However, each part of the model will be isolated in a separate figure in order to be viewed more clearly and analysed accordingly.

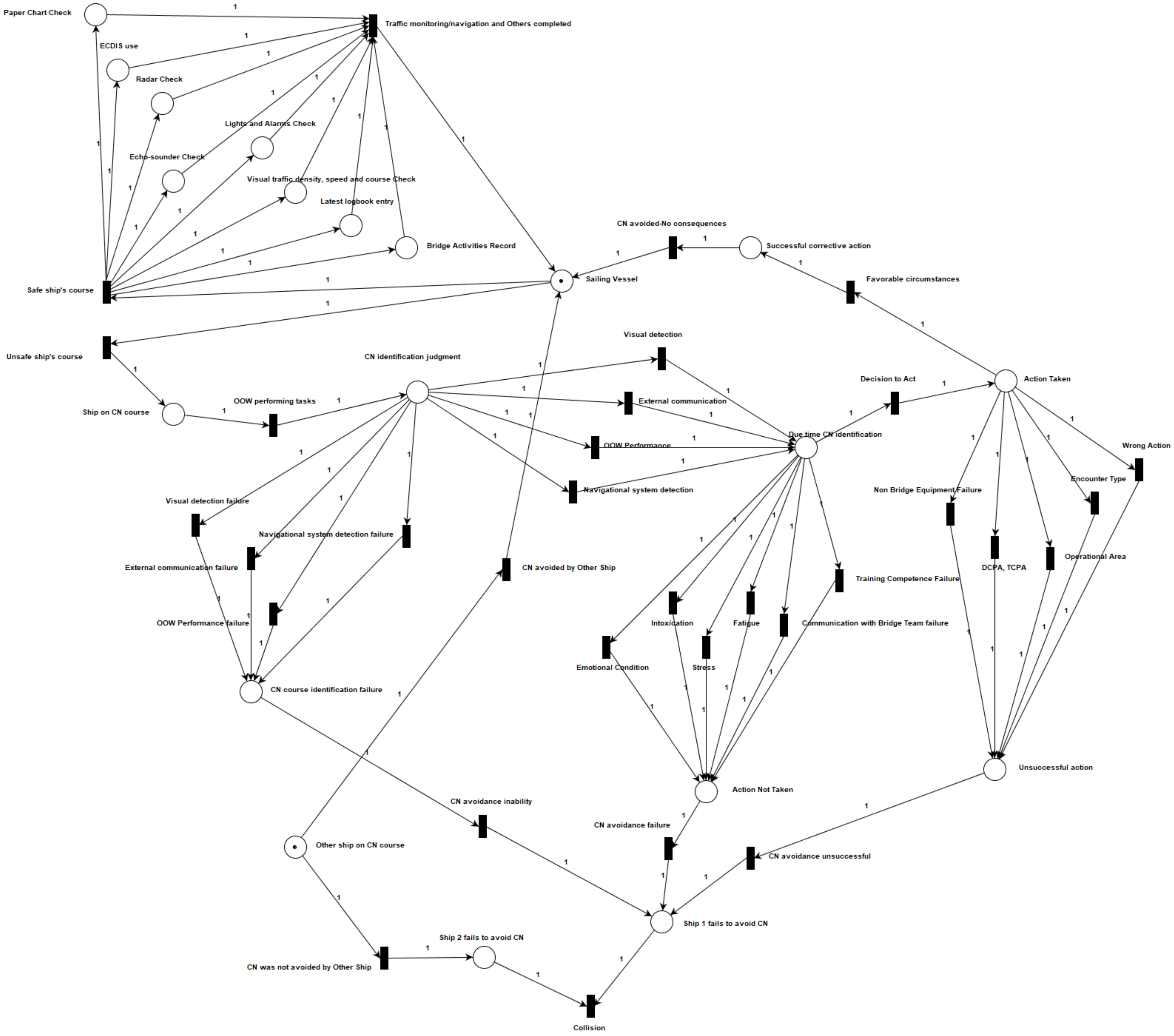


Figure 6.2: The developed PN model

The set-up model is a PN model. Each state of the collision process is displayed by a place and each event by a transition. As it has already been stated, places are connected with transitions by arcs and vice versa. The collision probability is calculated according to the PN probability calculation that is presented in the paper of Philippi et al. (Philippi et al., 2006). The calculation of the collision probability will be analysed in the sequel. The initial state of the PN model is considered to be the vessel's sailing and thus, a token is put into the place "Sailing vessel". After this state, it should be decided whether the ship's course is safe or unsafe.

When the vessel's sailing is characterised as safe, what is presented in the model is the duties that are performed by the OOW. Among others, the following are included in the navigational duties of the OOW and the duties that are related to traffic monitoring: the use of ECDIS, the paper chart check, the radar check, the echo-sounder check, the lights and alarm check, the visual traffic density, the speed and course check. The OOW has other duties, too, such as the latest logbook entry check and the record of the bridge activities (Deligiannis, 2017; Marine Insight, 2019b). It is obvious that the master's deputy has numerous responsibilities, but his aforementioned duties were considered to be some of the most important. The described part of the model is cited below (see Figure 6.3). When the performance of the duties of the OOW is completed, and given the fact that the vessel is sailing safely, the PN model returns to its initial form, with a token put in the place "Sailing vessel".

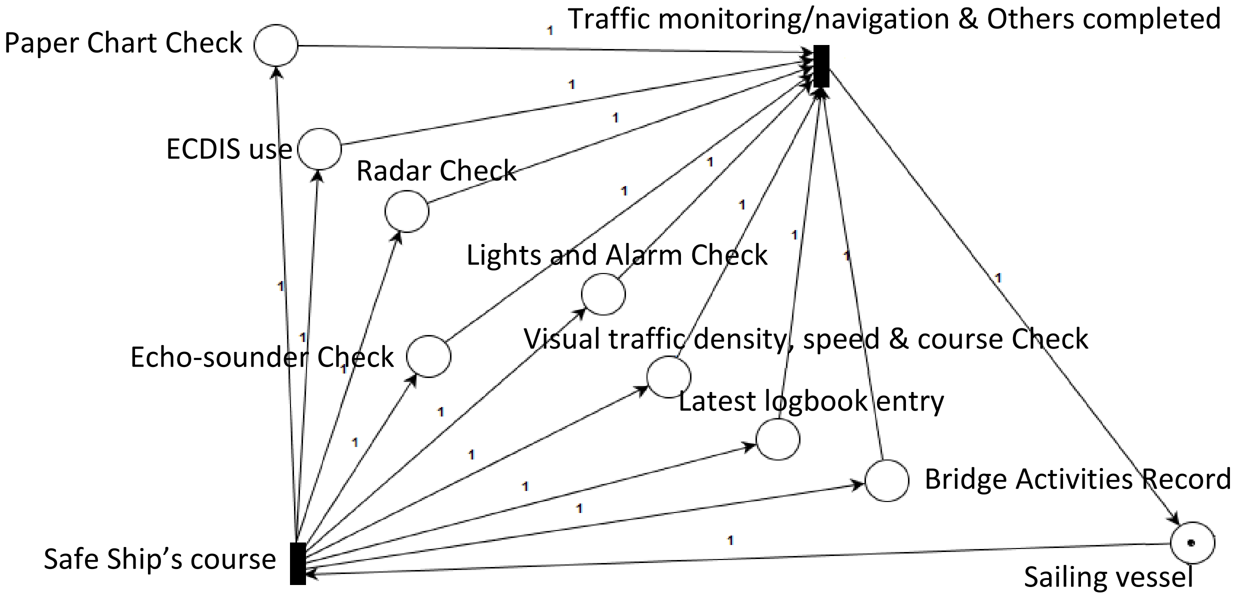


Figure 6.3: The performance of the duties of the OOW when the vessel's sailing is characterised as safe.

However, the vessel might not be sailing safely. If the vessel's route is changed, from secure to unsafe, then she is considered to be on a collision course. At this point, it is worth noting that, when the vessel starts sailing unsafely, the OOW is not aware of the collision situation and this is the reason why, at least at the beginning, none of his actions is corrective. The duties of the OOW continue being performed normally, as if the vessel was sailing safely, although her course is now “unsafe”. Obviously, at the same time the vessel keeps being on a collision course.

The next stage that is presented in the model is the one where a collision course identification should be done. As it is easily understood, there are two possible scenarios: Either the situation is recognized in due time by the OOW, or the collision course identification is unsuccessful. If the collision course is not identified at this stage by our OOW, it is assumed that nothing can be done by our side to avoid the collision. Thus, the collision accident is inevitable, if, of course, similar conditions prevail on the other vessel. If, on the other hand, the collision course is identified, the avoidance of the accident is still not ensured. However, it might be avoided in the following stages. Both scenarios are influenced by specific determinant factors that are presented subsequently.

The materialization of some factors might render the OOW not able to identify the collision course. The determination of these factors was based on the paper of Sotiralis et al. (Sotiralis et al., 2016). A factor that might impose the collision identification failure is the OOW’s failed performance, which means that, the process of conducting his duties is not completed correctly. For example, the nearby vessel might be detected in the ECDIS, but the OOW does not notice it or he could not understand it. The OOW might also turn off an emergency alarm either by accident or because he is not able to recognise the sound and thus fail to perceive the forthcoming collision. The optical detection of the approaching vessel might fail, too. The ability of the OOW to spot the other vessel is strictly connected with the weather conditions, the existence of day light and the experience of the observer.

Another fact that might lead to the collision identification failure is the unsuccessful external communication. As the vessels are coming closer one to another, an external factor might try to inform the vessel for the possible collision accident, but finally the communication is not able to occur. What might also happen, is the failure of the navigational system detection. However, even if the situation is the aforementioned, the OOW should be able to detect the collision using other means that are already mentioned (visual detection, external communication) and, above all, he should be able to recognise the system malfunction and act immediately.

However, the prevailing collision course might be recognised, despite the initial adversities. The success of only one of the aforementioned factors is enough so as the OOW to realise the situation: The OOW might achieve seeing the other vessel or understand it while performing his tasks, an external factor might succeed in informing the vessel for the forthcoming collision or the navigational system might detect the approaching vessel and thus inform the OOW. Of course, in order to reach the next level, which is the “Collision identification in due time”, the OOW should have some time to act.

The part of the model from the moment the vessel's course is stated as "unsafe" until the final judgement of the collision identification is cited below (Figures 6.4 and 6.5). In Figure 6.4 all the factors that might lead to "collision identification failure" are depicted and in Figure 6.5 are as well depicted the factors that result in "collision identification in due time". It is worth noting that, from the moment the vessel in on collision course and the OOW should recognise it (the place "CN identification judgement" is filled with a token) only one of the aforementioned factors will be enabled, which will determine the fate of the collision identification. The evolution of the situation, if the OOW finally manages to recognise the collision course, will be presented subsequently.

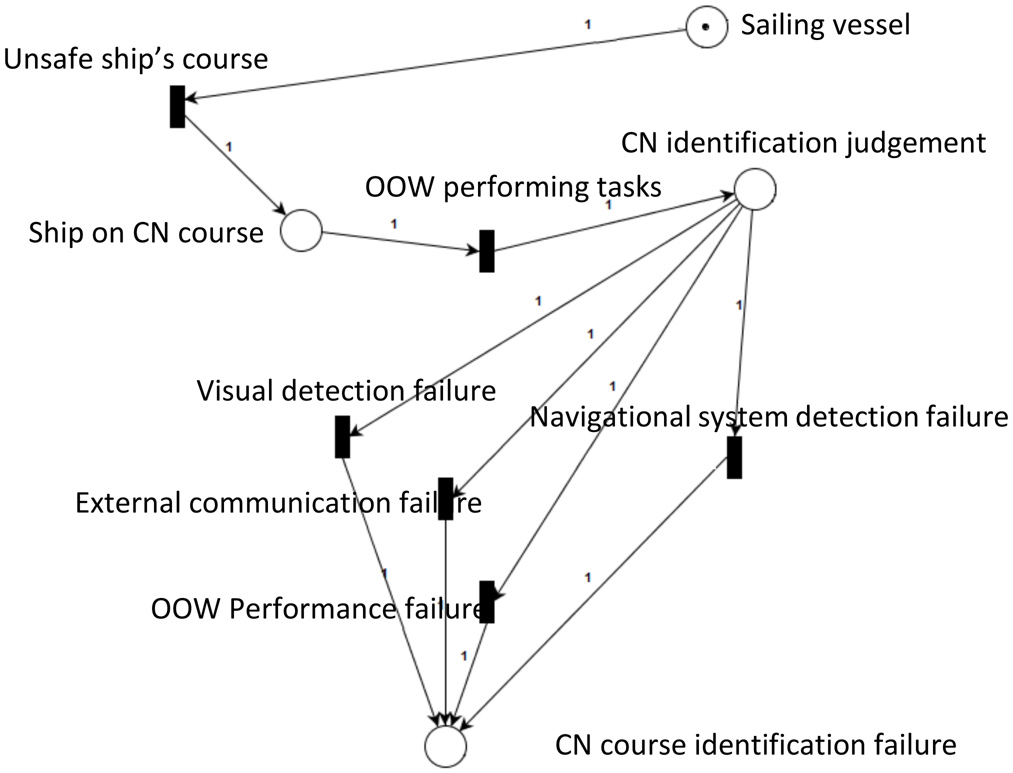


Figure 6.4: The factors that lead to the collision identification failure, since the vessel is being on a collision course.

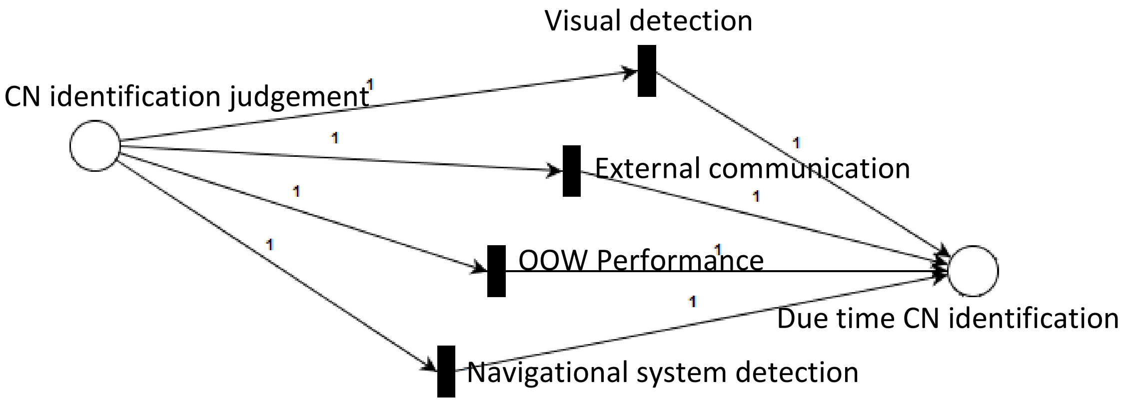


Figure 6.5: The factors that lead to the collision identification in due time, since the vessel is being on a collision course.

"Collision identification in due time" does not guarantee the avoidance of the collision. The time the OOW recognises the state of affairs, he should take action and, more than this, the taken action should be both correct and successful.

Given that the collision course is identified, the OOW might still stay inactive or the intended action might not be successfully accomplished. There are numerous reasons for the aforementioned possible evolutions, which are analysed below. It is important highlighting that, the inactivity of the OOW will, at this stage, impose the collision accident.

The judgment and the efficiency of the OOW are strictly connected with his personal condition. The factors that form the "personal condition" of the OOW are his psychological state, the intoxication, the levels of anxiety and tiredness. All the personal factors that are mentioned above might set the OOW unable to act in this critical moment and the collision is then unavoidable.

One more factor that is connected both with the OOW and with the training process, is the adequacy of his training skills and the relative knowledge that the OOW has acquired. Throughout the training process, the OOW might fail to understand which are the essential movements that should be taken while the vessel is on a collision course. The training process might even be insufficient. Thus, at the crucial moment, the OOW stays inactive.

The necessary movement might not be taken due to reasons that are not directly related to the OOW. Sometimes, an action should be taken by a total of other crew members who are on the Bridge. The communication failure between them is a serious matter which might result in no action undertaking. In fact, there have been vessel collision accidents that are an outcome of communication problems (The Nautical Institute, 2015). The OOW might order the corrective collision avoidance action, but the person who should act might fail to understand what should be done or when. The communication between them then fails, the necessary action is not taken, and the collision avoidance fails.

However, if the factors that are mentioned above do not constitute an obstacle, then the action undertaking is decided. In the following figure, the factors that lead to either the action undertaking success or the action undertaking failure are presented (see Figure 6.6).

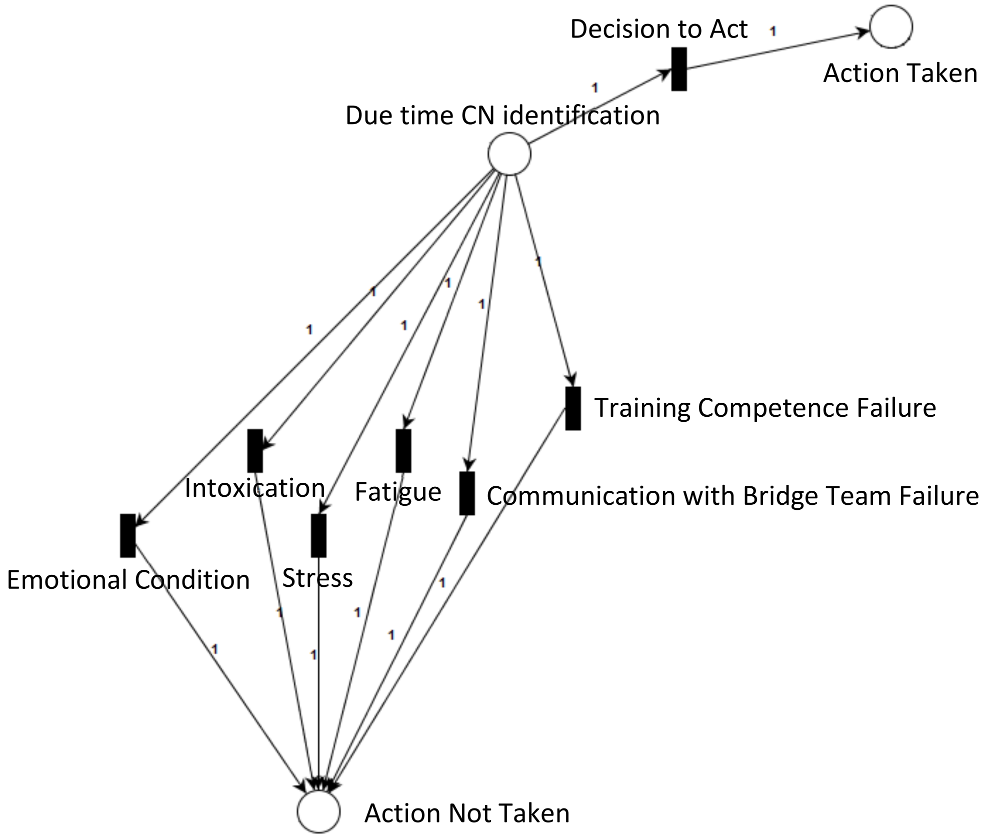


Figure 6.6: The factors that lead to either the action undertaking success or the action undertaking failure.

If the OOW finally decides to act, the only thing that matters is the success of the taken action. If the action is proved to be unsuccessful, the vessel suffers the collision accident. But if the action is successful, this is finally the moment when the collision is avoided. The factors that result in each state are respectively analysed below.

Synoptically, as it has been described already, the vessel's course is unsafe, the OOW has managed to identify the collision course and, in due time he has decided to act. Thus, the action is finally taken but there are some factors that might force the action to be ineffective. It is obvious that, if the taken action is wrong, it is failed, and it will not result in collision avoidance. For example, if the necessary action is the rudder's turn, but, instead, the OOW, decides to reduce the vessel's speed, the taken action is wrong and thus unsuccessful. However, if the taken action is correct but nevertheless unsuccessful, the factors that impose the failure are not connected with the action itself.

One leading factor for action unsuccessfulness is the failure of the necessary non-bridge equipment for collision avoidance which might occur the moment the equipment should be used. For example, if the OOW should turn the rudder but the critical moment the rudder is lost or broken, the action will not be completed. The operational area of the vessel also has an impact on her maneuverability (Shu et al., 2013). Obviously, the narrowest or the shallower a place, the harder and more dangerous it is for a vessel to move. The critical moment, the difficulty of maneuverability might force the collision.

One more factor that has an effect on the success of the taken action is the type of vessels' encountering (overtaking, head-on, crossing), in combination, of course, with the distance between them, which might have become very short. "Very short distance" means a distance value limit, according to which, at a distance value less than this, the collision accident is considered to be inevitable. In the context of the present thesis, 1 NM is considered to be this distance value limit. The distance of 1 NM has also been highlighted in other, previous studies (Hao and Zhao, 2019; Koldemir, 2009; Porathe, 2019). At this point it is worth noting that, the risk of collision is considered to exist only when the distance between the vessels that are about to collide becomes less than 3 NM. Thus, if the distance between the vessels is more than 3 NM, the ship's course is considered to be exclusively "safe".

The aforementioned factors, which might impose the action's undertaking failure, are considered to be independent one with another. The factors' independency means that the action of the OOW might be proven unsuccessful, only if a single causal factor is enabled.

However, if the circumstances are allowable, the action will result in collision avoidance and both vessels will return in the initial state of "sailing", and, more than this, if no other adversities appear, the vessels will sail "safely". All the factors that affect the two possible outcomes of action undertaking, "successful corrective action" or "unsuccessful action", are presented in the following figure (Figure 6.7).

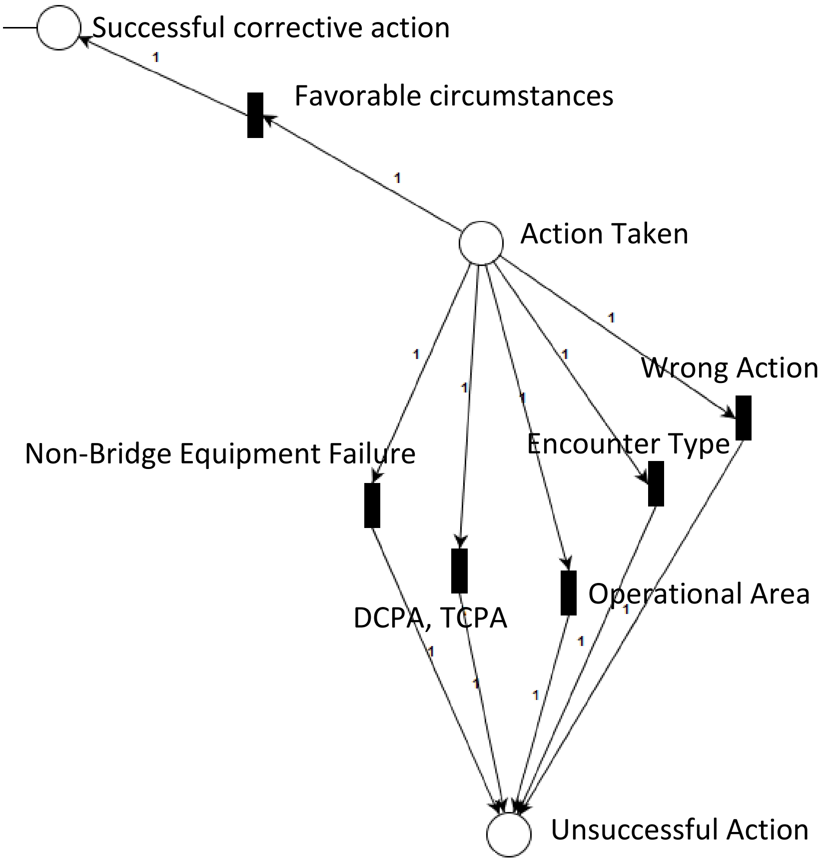


Figure 6.7: The factors that lead to the two possible outcomes of action undertaking: “successful corrective action” or “unsuccessful action”.

Some details of the model are worth been clarified. According to the following figure (Figure 6.8), the state of “Ship 1 fails to avoid CN” is true if at least one of the following states have been previously happened: “Collision course identification failure”, “Action Not Taken” or “Unsuccessful Action”.

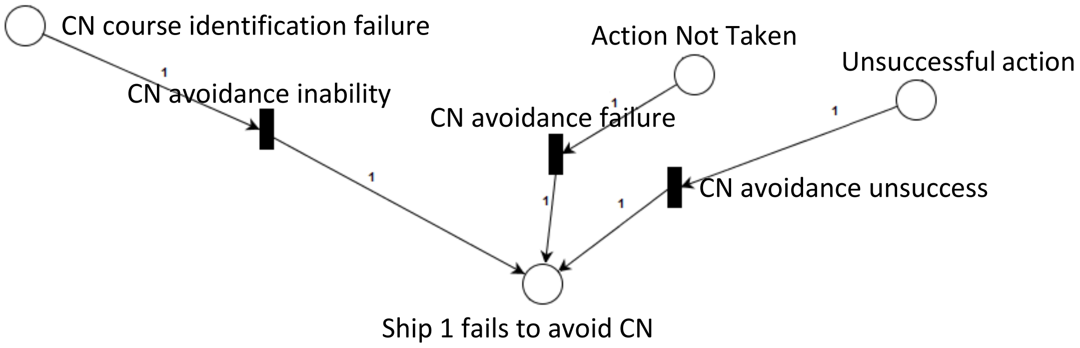


Figure 6.8: The three possible places that should previously have been enabled in order for “Collision” to happen: “Collision identification failure”, “Action not taken” or “Unsuccessful action”.

However, as it has been mentioned above, at the final stage of collision avoidance judgement, the reaction of the other vessel is included. Thus, in order for the collision to occur, the collision avoidance procedure should have been failed by the side of the other ship, too. The integrated depiction of the collision avoidance failure is presented in Figure 6.9. The place "Ship 2 fails to avoid CN" should be filled with a token and for "Collision" to be able to happen, "Collision course identification failure" or "Action Not Taken" or "Unsuccessful Action" should have already been applied, too. The three aforementioned states-places concern the reaction of our vessel ("Ship 1"), which is considered to be the result of the actions of the (our) OOW.

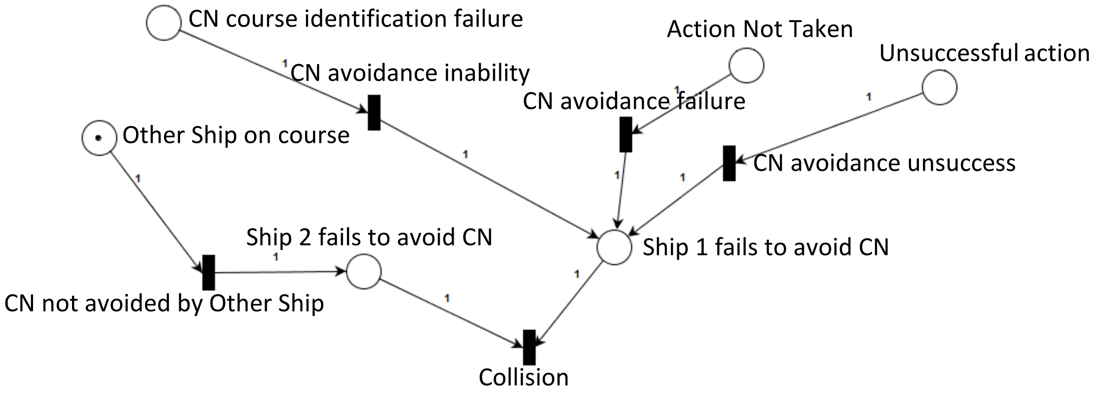


Figure 6.9: The inclusion of the other vessel's collision avoidance management in the "Collision" judgement.

If a token is not put into the place "Ship 2 fails to avoid CN", it means that the other vessel has managed to avoid the collision. The collision will not happen finally, if at least one of the involved vessels manages to success in collision avoidance. And still, if a token is put into the place "Ship 2 fails to avoid CN" but our OOW finally avoids the collision, the accident will not occur.

From the moment the vessel sails unsafely, there are two graphical scenarios for collision avoidance: "Collision avoided-No consequences" or "Collision avoided by other ship". Both scenarios are represented by a transition and, when they are enabled, they force the throwing of a token into the place "sailing vessel", which means that the course of the ship has returned to its initial safe, sailing state.

The enablement of the transition "Collision avoided-No consequences" presupposes that our OOW has taken a collision avoidance action, which was achieved with success. The other ship might also success in avoiding the collision, but the actions of the other ship are not presented. The initial state of the examined other ship is "Other Ship on Collision course", which is depicted by a place filled with a token. Two possible scenarios exist, concerning the other vessel's collision avoidance fate: either "Collision avoided by Other Ship", or "Collision was not avoided by Other Ship". The aforementioned possible scenarios are depicted in the developed model as transitions. The analytical state of the other ship and her total collision course progress is not included in the developed model, because, as it has already been highlighted, the whole analysis of the model is focused on the actions of our OOW. Thus, the collision course management by the side of our vessel is basically studied and therefore it is the only one fully presented. In Figure 6.10, a depiction of the aforementioned statements is presented.

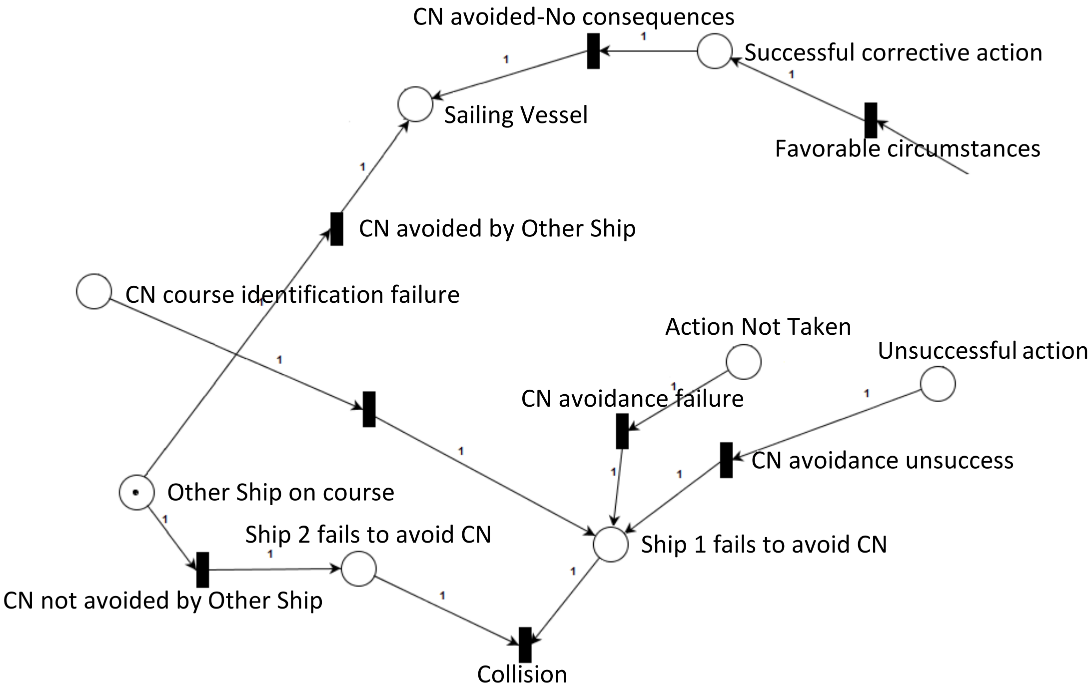


Figure 6.10: The final stage of judgement, including the reaction of the Other vessel.

Two tokens are put initially in the PN model: one token in the place “Sailing vessel” and one token in the place “Other Ship on CN course”. The place “Sailing vessel” concerns the initial state of our vessel. However, the initial state of the other vessel is considered to be “Other Ship on CN course”, because the initial sailing of the other vessel is not examined nor analysed. Only the series of actions of our vessel matter.

7. Calculation of the Collision Probability

7.1. Introduction

The developed PN model results in the calculation of a collision probability, which will be performed according to probability calculations that that have been made previously, according to the international literature (Berghout and Bennoui, 2015; Lautenbach, 2007; Lautenbach and Pinl, 2007; Philippi et al., 2006).

In the following figure (Figure 6.11), the PN model that is examined in the work of Philippi et al. (Philippi et al., 2006) is depicted. The probability that is calculated is the probability that corresponds to the place “acde”. The place “acde” enables the transition t_{18}. The possible transitions that should be enabled in order for the place “acde” to be filled with a token are the transitions t_3, t_4, t_7 and t_8. The aforementioned four transitions form a sum of multiplications which is the required probability. The transition t_8 is enabled only if both places “lo” and “igir” are filled with a token. The places “lo” and “igir” are filled with a token only if the transitions t_{16} and t_{14} are enabled, respectively. The multiplication of probabilities that derives from the enablement of transition t_8 is $P(t_{16})\cdot P(t_{13})\cdot P(t_8)$. Respectively, the multiplication of probabilities that derives from the enablement of transition t_7 is $P(t_{16})\cdot P(t_{13})\cdot P(t_7)$, the multiplication of probabilities that derives from the enablement of transition t_4 is $P(t_{15})\cdot P(t_{14})\cdot P(t_4)$ from t_3 is $P(t_{15})\cdot P(t_{13})\cdot P(t_3)$. The aforementioned multiplications should be sumed up all together and then multiplied with the probability of the transition t_{18}, $P(t_{18})$, which is the final enabled transition from the moment the place “acde” is filled with a token. Thus, the required probability is the following sum of multiplications:

$$P_{acde} = P(t_{16})\cdot P(t_{14})\cdot P(t_8)\cdot P(t_{18}) + P(t_{16})\cdot P(t_{13})\cdot P(t_7)\cdot P(t_{18}) +$$
$$+P(t_{15})\cdot P(t_{14})\cdot P(t_4)\cdot P(t_{18}) + P(t_{15})\cdot P(t_{13})\cdot P(t_3)\cdot P(t_{18})$$

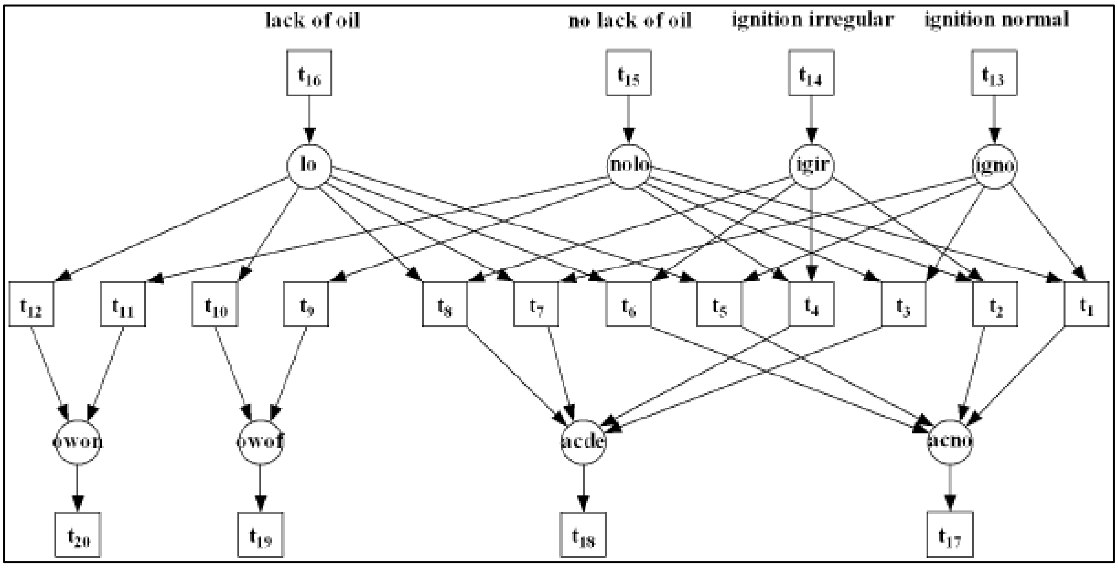
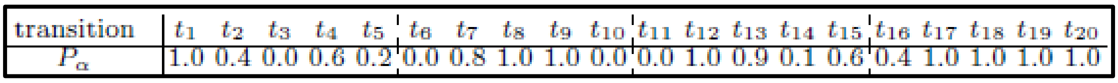


Figure 7.1: The PN model that is examined in the work of Philippi et al..

The values $P_a(t_i)$, i=1, 2, 3, …, 20, of the aforementioned probabilities are listed in the following figure, which appears in the research of Philippi et al..



transition	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}	t_{13}	t_{14}	t_{15}	t_{16}	t_{17}	t_{18}	t_{19}	t_{20}
P_α	1.0	0.4	0.0	0.6	0.2	0.0	0.8	1.0	1.0	0.0	0.0	1.0	0.9	0.1	0.6	0.4	1.0	1.0	1.0	1.0

Figure 7.2: The values of probabilities that are used in the work of Philippi et al. for the final probability calculation.

Thus, the final calculated probability is

$$P_{acde} = 0{,}4 \cdot 0{,}1 \cdot 1 \cdot 1 + 0{,}4 \cdot 0{,}9 \cdot 0{,}8 \cdot 1 + 0{,}6 \cdot 0{,}1 \cdot 0{,}6 \cdot 1 + 0{,}4 \cdot 0{,}9 \cdot 0 \cdot 1$$

$$P_{acde} = 0{,}04 + 0{,}288 + 0{,}036 + 0$$

$$P_{acde} = 0{,}364$$

In the paper of Berghout and Bennoui (Berghout and Bennoui, 2015) the developed PN model consists of two subsystems, which are presented in Figure 7.3. The PN model examines the actions and reactions of a father and his daughter: The father might buy a gift for his daughter and she might like it, then she might use it or be happy or get good grades. If she is happy, her father will be, as well. If she gets good grades or she behaves well, her father will be proud. Each of these states (depicted as transitions in Figure 7.3) has been assigned a probability value. The probability values are presented in the paper and in Figure 7.4.

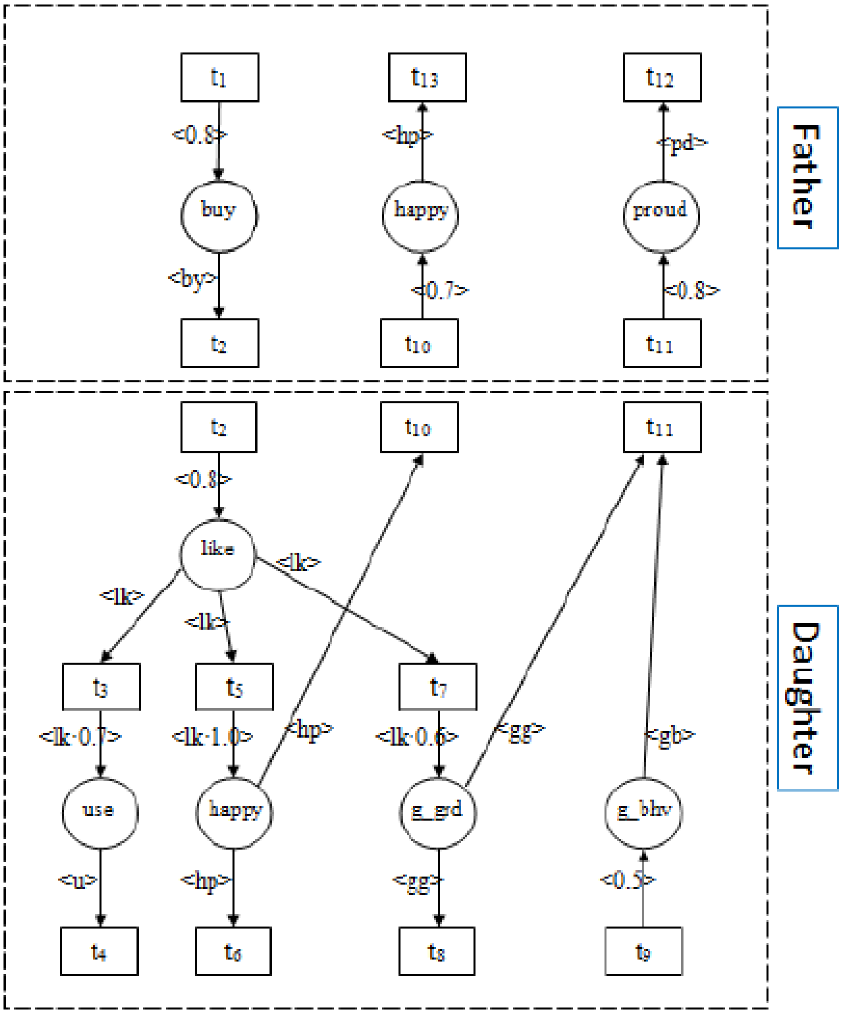
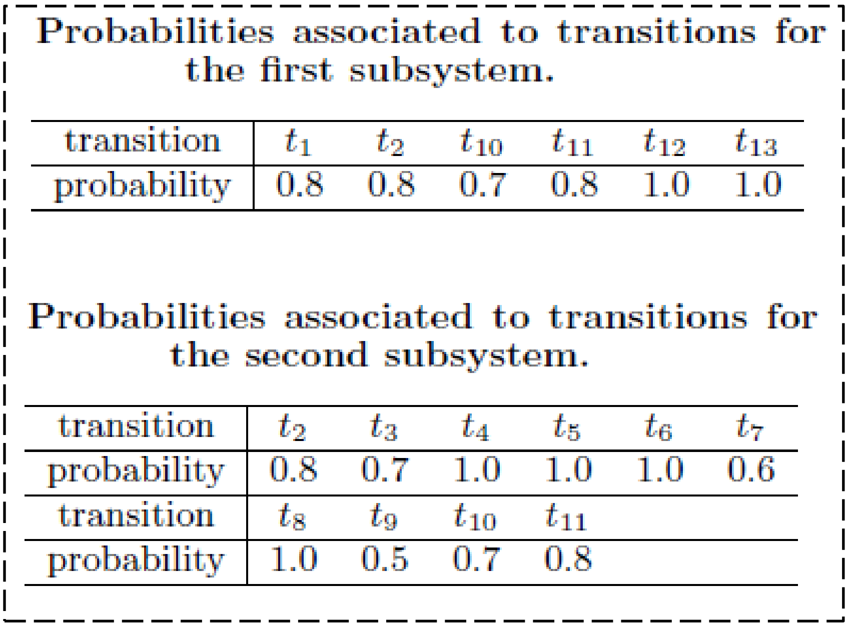


Figure 7.3: The developed PN model in the paper of Berghout and Bennoui.



Probabilities associated to transitions for the first subsystem.

transition	t_1	t_2	t_{10}	t_{11}	t_{12}	t_{13}
probability	0.8	0.8	0.7	0.8	1.0	1.0

Probabilities associated to transitions for the second subsystem.

transition	t_2	t_3	t_4	t_5	t_6	t_7
probability	0.8	0.7	1.0	1.0	1.0	0.6
transition	t_8	t_9	t_{10}	t_{11}		
probability	1.0	0.5	0.7	0.8		

Figure 7.4: The probability values that are assigned to the transitions of the PN model of Berghout and Bennoui.

The requested probability value is the probability that the father is proud. The goal transition connected with the possibility that the father is proud is t_{12}. Transitions t_1 and t_9 indicate the two possible paths that should be followed, in order to reach (enable) t_{12}. Thus, the requested probability is equal to:

$$P(t_{12}) = P(t_9) \cdot P(t_{11}) + P(t_1) \cdot P(t_2) \cdot P(t_7) \cdot P(t_{11})$$

$$P(t_{12}) = 0.5 \cdot 0.8 + 0.8 \cdot 0.8 \cdot 0.6 \cdot 0.8$$

$$P(t_{12}) = 0.4 + 0.3072$$

$$P(t_{12}) = 0.7072$$

In both of the aforementioned probabilistic PN models, the goal transitions receive the probability value of 1. However, these transitions actually carry two values, one considering the probability that "enters" and the other considering the probability that "exits" the transition. The value that corresponds to the exit of the transition (t^{out}) equals to 1. The value that corresponds to the entrance (t^{in}) might be calculated.

The probabilistic PN models of Philippi et al. and Berghout and Bennoui are simple probability calculation examples, which will be the reference point for the complicated probability calculation of the developed PN model that is presented in the current paper. The requested probability is analytically calculated in the following section.

7.2. Determination of the parameters involved in the vessel collision probability calculation

In the developed PN model, numerous transitions are included, as it might be highlighted in Figure 6.2. At this point, it is worth noting that, the part of the model that is connected to the "Safe Ship's course" (see Figure 6.3) as well as the part of the transitions which impose the collision avoidance success of the vessels (see Figure 7.5), do not contribute to the collision probability calculation. It is obvious that, in order for a vessel to collide with another, an "Unsafe Ship's course" should have been preceded. Thus, the performance of the duties of the OOW when the vessel's sailing is characterised as "safe" (see Figure 6.3) is a quality depiction that is included in the developed PN model. The transitions that are connected to the collision avoidance success ("CN avoided by Other Ship", "Successful corrective action", "CN avoided-No consequences") are also added to the model only for qualitative reasons. If at least one of the vessels that are on the collision course finally avoids the collision, then the accident will not happen and thus, the collision avoidance part is not connected with the calculations that concern the collision accident.

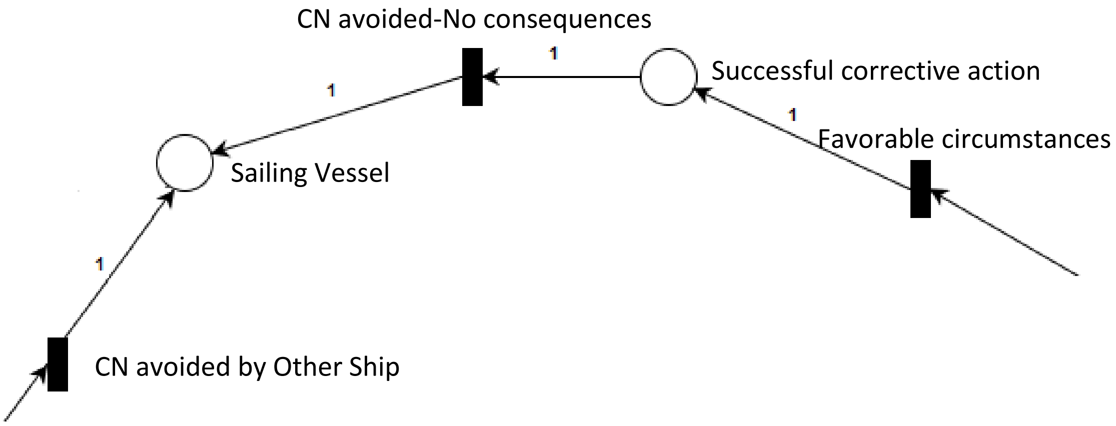


Figure 7.5: The transitions which impose the vessels collision avoidance success do not contribute to the calculation of the collision probability.

The collision probability will be analytically presented and calculated. Each of the transitions that appear in the developed model has a probability assigned to it. As the names of the transitions are long and complicated, new names, t_1, t_2, t_3, …, t_{26} are given to each transition. In the following table (Table 7.1), the new names of the transitions and their definitions are presented.

Table 7.1: The names and descriptions of the transitions of the PN model

Transition Name	Transition Description
t_1	Unsafe ship's course
t_2	OOW performing tasks
t_3	Visual detection failure
t_4	External communication failure
t_5	OOW performance failure
t_6	Navigational system detection failure
t_7	Visual detection
t_8	External communication
t_9	OOW performance
t_{10}	Navigational system detection
t_{11}	Emotional condition
t_{12}	Intoxication
t_{13}	Stress
t_{14}	Fatigue
t_{15}	Communication with Bridge Team failure
t_{16}	Training competence failure
t_{17}	Decision to Act
t_{18}	Non-bridge equipment failure
t_{19}	DCPA, TCPA
t_{20}	Operational area
t_{21}	Encounter type
t_{22}	Wrong action
t_{23}	Collision avoidance inability
t_{24}	Collision avoidance failure
t_{25}	Collision avoidance unsuccessful
t_{26}	Collision was not avoided by Other Ship
t_{27}	Collision

7.3. Quantification of the parameters involved in the vessel collision probability calculation

At this point, it is worth noting that, some of the parameters that are involved in the developed PN model are also presented in the paper of Sotiralis et al. (Sotiralis et al., 2016) (see Figure 7.6). Each of the parameters, which contributes to the vessel collision probability, has a probability value assigned to it. All of the probability values are presented below, together with their literature source. The probabilities t_{26} and

t_{27} do not have an assigned value, as it will be highlighted subsequently. However, t_{26} will be defined and t_{27} is actually the requested collision probability value and it will be calculated.

Figure 7.6: The BN model that was developed in the paper of Sotiralis et al.

The probability that is calculated in the present thesis is the probability that concerns the event of collision. At this point, it is worth noting that 3 scenarios will be considered, regarding the vessels' encounter type: head-on, crossing and overtaking. Thus, 3 probability values will be calculated. In each of the three scenarios, the probability value that is assigned to the transition t_{21} (encounter type) will be different. All of the other transitions will receive constant probability values.

In order to have collision, an unsafe (a collision) course of the vessel should have been preceded. According to the experts' judgement, a vessel is exposed to an unsafe course every 1000 courses, which means that, the probability of the transition t_1 is equal to 0.001.

Assuming that the OOW is unaware of the collision course, he keeps performing his duties on the Bridge. The unawareness of the OOW is very important at this stage, because the needed probability is t_2, which is the probability of the OOW start to performing tasks, is the same probability as if the vessel was sailing under a safe course, and as if the situation, regarding the time pressure, was normal. The probability of the transition t_2 is equal to 0.99, a value which was acquired by the experts' judgement.

After the OOW has started performing the necessary tasks, he should finally recognise the state of affairs. However, if any of the transitions t_3, t_4, t_5 or t_6 is enabled, the OOW will not manage to identify the situation and act accordingly.

The probability of visual detection failure (t_3) is equal to 0.14 (chosen from expert judgements) and the probability of external communication failure (t_4) is equal to 0.7 (Papamichalis, 2008). The OOW performance failure (t_5) probability is 0.075 and the navigational system detection failure (t_6) probability is equal to 0.032 (Vagias, 2010).

The transitions t_3, t_4, t_5 and t_6, the values of which were given above, constitute the OOW unable to identify the collision situation. The transitions t_7, t_8, t_9 and t_{10}, on the other side, are considered to lead the OOW to "Collision course identification in due time".

As it has already been described above, assuming, of course, that the OOW has some time available to act (normal ship operation), the success of only one of the aforementioned factors is enough for the identification of the collision situation. The probability of visual detection (t_7) is equal to 0.86 ($P_{t7} = 1 - P_{t3}$) and the probability of detection due to the successful (above standard) OOW's performance (t_8) is 0.925. An external factor might manage to inform the vessel for the forthcoming collision (t_9) with a probability that reaches the value of 0.3, or the navigational system might detect the approaching vessel (t_{10}) and thus inform the OOW with a probability value of 0.968.

The values of the probabilities that correspond to the transitions t_1- t_{11} are presented in Table 7.2.

Table 7.2: The probability values of the transitions t_1, t_2, t_3, …, t_{10}

Transition	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}
Probability	0.001	0.99	0.14	0.7	0.075	0.032	0.86	0.925	0.3	0.968

If the OOW manages to recognise the collision course in due time, the next stage of the developed model will be reached. The aforementioned stage is about the OOW's ability to assess the situation correctly: either the OOW decides not to act, due to specific factors (t_{11}-t_{16}), or he decides to act (t_{17}). The transitions t_{11}, t_{12}, t_{13}, t_{14}, t_{15} and t_{16} are connected directly or indirectly to the OOW.

Transitions t_{11}-t_{14} are highly dependent on the OOW's personal state and judgement. More specifically, the OOW's emotional condition (t_{11}) might lead to the action undertaking nonfulfillment with a probability that receives the value 0.01. The probabilities of the intoxication of the OOW (t_{12}), the stress condition of the OOW (t_{12}) and the fatigue of the OOW (t_{15}) are equal to 0.02 (Akhtar and Utne, 2014), 0.24 (Vagias, 2010) and 0.04 (Papamichalis, 2008), respectively.

The communication failure between the OOW and the Bridge Team (t_{15}) is an event that might happen with a probability equal to 0.207, according to the experts, while the probability of the OOW's training competence failure (t_{16}) is 0.258 (Vagias, 2010). It is obvious, that if any of the transitions t_{11}-t_{16} is enabled, the (our) OOW will fail to avoid the collision.

However, there is a high potential of the OOW deciding to undertake an action. Actually, the OOW's correct situation assessment (t_{17}) has a probability value of 0.996 (Sotiralis et al., 2016).

The probabilities of the factors that determine the OOW's decision to act are listed below in Table 7.3.

Table 7.3: The probability values of the transitions t_{11}, t_{13}, t_{14}, …, t_{17}

Transition	t_{11}	t_{12}	t_{13}	t_{14}	t_{15}	t_{16}	t_{17}
Probability	0.01	0.02	0.24	0.05	0.207	0.258	0.996

Even if the OOW decides to act, which means that transition t_{17} is enabled, still it is not sure that the collision will be avoided. The probabilities of the factors that might lead to collision avoidance failure should be acquired, because the final required probability value is the ship collision probability. If the circumstances are favorable, the collision will be avoided, but, obviously, the probability of this fact does not contribute to the required final calculation. As it has already been highlighted, the depiction of the "Favorable circumstances" transition is presented in the model only for qualitative reasons.

The factors that might impose the failure of the action are represented by the transitions t_{18}-t_{22}. The probability of the failure of the non-bridge equipment (t_{18}) is equal to 0.0001092 (=1.09E-04) (Det Norske Veritas, 2006). Another factor which might prevent the action's success at this stage, is the short left DCPA. "Short DCPA" is considered to be a relative distance between the vessels, which is, in average, less than 1 NM. Obviously, this value of the distance between the vessel depends on numerous factors (operational area, speed, ship type, visibility, weather conditions etc.). The possibility of the aforementioned factor (t_{19}) is equal to 0.001, according to the judgment of the experts.

The vessel's operational area might contribute to the action's unsuccessfulness (t_{20}) with a probability that gets the value 0.33. The aforementioned value indicates the fact that all of the possible operational areas (terminals, congested waters and open sea) are considered to have the same happening probability. Moreover, the vessel's operational area is not regarded as a factor which strongly affects the final calculation of the collision probability, because it is considered that the safety measures in each of the operational areas are taken accordingly. It has already been highlighted, that most shipping accidents happen due to a human error. However, even if the vessels sail in a restricted area and the distance between them is very small, the OOW then is by far more alerted, or an external pilot might have undertaken the navigation of the vessel. The PN model is a generalised model, which means that the collision probability calculation is considered to concern every potential scenario (for all the ship types and sizes, weather conditions, operational areas etc.). Thus, all of the probabilities that are used to calculate the final collision probability are respectively generalised.

The encounter type according to which the vessels are approaching one another (t_{21}) might also lead to the action failure with a probability value that is differentiated, according to the three possible encounter types. Thus, for the case of a head-on collision, t_{21} gets the probability value of 0.2, for the case of a crossing collision, 0.58, and for the case of an overtaking encounter type, 0.22 (Psaraftis et al., 1998). The last factor that will impose the action's failure is the undertaking of a wrong action. The probability that the OOW's action is wrong (t_{22}) is equal to 0.004 (Det Norske Veritas, 2006; Vagias, 2010).

In Table 7.5 the values of the probabilities that are assigned to the transitions t_{18}, t_{19}, t_{20}, t_{21} and t_{22} are presented.

Table 7.4: The probability values of the transitions t_{18}, t_{19}, t_{20}, t_{21} and t_{22}

Transition	t_{18}	t_{19}	t_{20}	t_{21}			t_{22}
				Head-on	Crossing	Overtaking	
Probability	1.09E-04	0.001	0.33	0.2	0.58	0.22	0.004

The rest of the transitions (t_{23}-t_{26}) have also a probability value assigned to them. As it is highlighted in Table 7.6, the definition of the transitions t_{23}, t_{24} and t_{25} ("Collision avoidance inability", "Collision avoidance failure" and "Collision avoidance unsuccessful", respectively) is, theoretically, the same. However, the probability value that is assigned to the aforementioned transitions is not the same, because, actually, their meaning is very different.

Transition t_{23} is enabled only if the OOW has not managed to identify the collision course of the vessel, or, in other words, the OOW did not make a diagnosis of the situation (OOW's detection state: no detection). The probability value of t_{23} is equal to 0.834 (Sotiralis et al., 2016).

Transition t_{24} is enabled only if the OOW has managed to identify the collision course in due time, but, yet, he did not achieve taking an action in order to avoid it. Thus, the OOW detected correctly the situation, but he assessed it wrongly. The probability value of t_{24} is equal to 0.762.

Transition t_{25} is enabled only if the OOW has managed to identify the collision course in due time, then he decided to take an action in order to avoid it, but, finally, the action was proved unsuccessful. In other words, the OOW detected and assessed the situation correctly, but he finally failed to avoid the collision because the taken action was unsuccessful. The probability value of t_{25} is equal to 0.762

In Table 7.6 the probability values that are assigned to transitions t_{23}, t_{24} and t_{25} are presented.

Table 7.5: The probability values of the transitions t_{23}, t_{24} and t_{25}

Transition	t_{23}	t_{24}	t_{25}
Probability	0.834	0.762	0.762

Transition t_{26} is the transition with the assigned definition "Collision was not avoided by Other Ship". The final calculation of the collision probability takes into consideration both ships. The whole analysis of the PN model is focused on the actions of our vessel (OOW). However, it is assumed that similar conditions prevail on the other ship, which means that, the probability that our vessel fails to avoid the collision accident is considered to receive the same value with the probability that the other vessel fails to avoid the collision accident. Thus, for the final collision probability, $P_{collision}$, the following is true:

$$P_{collision} = f(P_1, P_2)$$

where P_1: the probability that our ship fails to avoid collision

P_2: the probability that the other ship fails to avoid collision

According to the assumptions that have been made,

$$P_1 = P_2$$

Moreover,

$$P_1 = f(P_a, P_b, P_c)$$

where P_a: the probability that our OOW failed to identify the collision course

P_b: the probability that our OOW failed to take an action

P_c: the probability that the action of our OOW was unsuccessful

The calculation of the collision probability will be divided into sections.

In the following figure (Figure 7.7), the probabilities P_a, P_b, P_c (red colour), P_1 (dark purple colour) and P_2 (green colour), which compose the collision probability, $P_{collision}$, are highlighted.

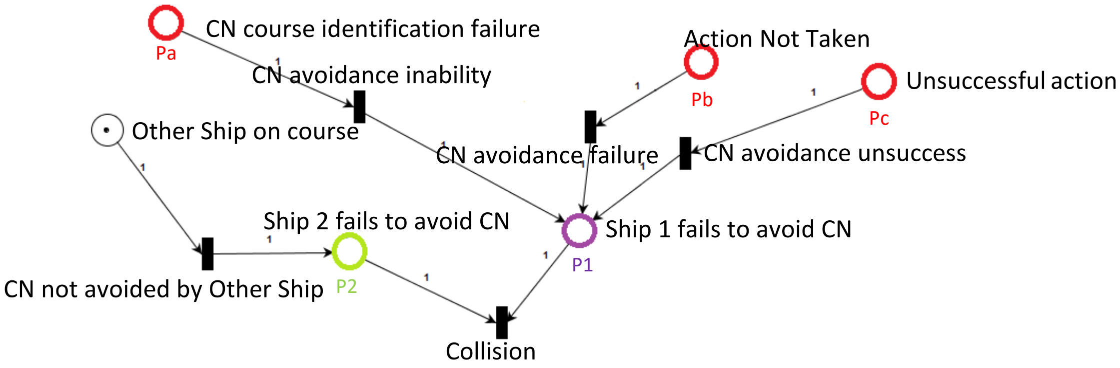


Figure 7.7: The probabilities that compose the collision probability

The calculation of the probabilities P_a, P_b and P_c, which form the probability of our vessel's (OOW's) collision avoidance failure (P_1), will be presented analytically.

7.4. Calculation of the vessel collision probability

As it has been already highlighted, the calculation of the vessel collision probability will be made according to the probability calculation that is presented in the paper of Philippi et al. (Philippi et al., 2006). The calculation of the aforementioned probabilities P_a, P_b and P_c, is analytically presented at this point.

a. The calculation of P_a

In Figure 7.8, the values of probabilities which should be considered in order to calculate P_a are highlighted with an orange colour. The calculation of P_a is the following:

$$P_a = P(t_1) \cdot P(t_2) \cdot P(t_3) \cdot P(t_{23}) + P(t_1) \cdot P(t_2) \cdot P(t_4) \cdot P(t_{23}) + \\ +P(t_1) \cdot P(t_2) \cdot P(t_5) \cdot P(t_{23}) + P(t_1) \cdot P(t_2) \cdot P(t_6) \cdot P(t_{23})$$

$$P_a = P(t_1) \cdot P(t_2) \cdot P(t_{23}) \cdot (P(t_3) + P(t_4) + P(t_5) + P(t_6))$$

$$P_a = 0.001 \cdot 0.99 \cdot (0.14 + 0.7 + 0.075 + 0.032) \cdot 0.834$$

$$P_a = 0.00078190002$$

$$P_a = 7.8190\mathrm{E} - 04$$

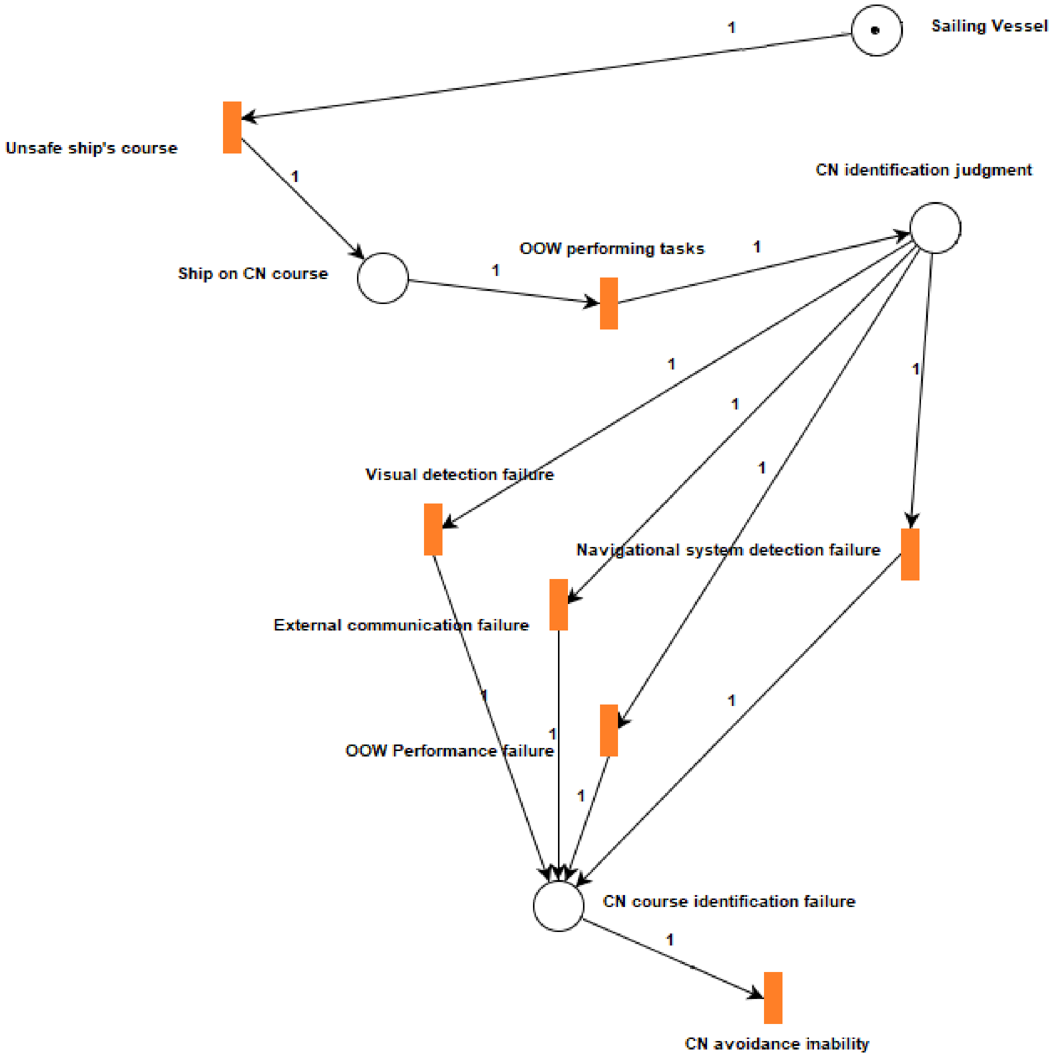


Figure 7.8: The probabilities which form P_a.

b. The calculation of P_b

In Figure 7.9, the values of probabilities which should be considered in order to calculate P_b are highlighted with a light purple colour. The calculation of P_b is the following:

$$\begin{aligned} P_b = {} & P(t_1) \cdot P(t_2) \cdot P(t_7) \cdot P(t_{11}) \cdot P(t_{24}) + P(t_1) \cdot P(t_2) \cdot P(t_8) \cdot P(t_{11}) \cdot \\ & \cdot P(t_{24}) + P(t_1) \cdot P(t_2) \cdot P(t_9) \cdot P(t_{11}) \cdot P(t_{24}) + P(t_1) \cdot P(t_2) \cdot P(t_{10}) \cdot \\ & \cdot P(t_{11}) \cdot P(t_{24}) + P(t_1) \cdot P(t_2) \cdot P(t_7) \cdot P(t_{12}) \cdot P(t_{24}) + P(t_1) \cdot P(t_2) \cdot \\ & \cdot P(t_8) \cdot P(t_{12}) \cdot P(t_{24}) + \ldots + P(t_1) \cdot P(t_2) \cdot P(t_{10}) \cdot P(t_{16}) \cdot P(t_{24}) \end{aligned}$$

$$P_b = P(t_1) \cdot P(t_2) \cdot P(t_{24}) \cdot \big(P(t_7) + P(t_8) + P(t_9) + P(t_{10})\big) \cdot$$

$$\cdot \left(P(t_{11}) + P(t_{12}) + P(t_{13}) + P(t_{14}) + P(t_{15}) + P(t_{16})\right)$$

$$P_b = 0.001 \cdot 0.99 \cdot 0.762 \cdot (0.86 + 0.3 + 0.925 + 0.968) \cdot$$

$$\cdot (0.01 + 0.02 + 0.24 + 0.05 + 0.207 + 0.258)$$

$$P_b = 0.0018079508799$$

$$P_b = 0.0018$$

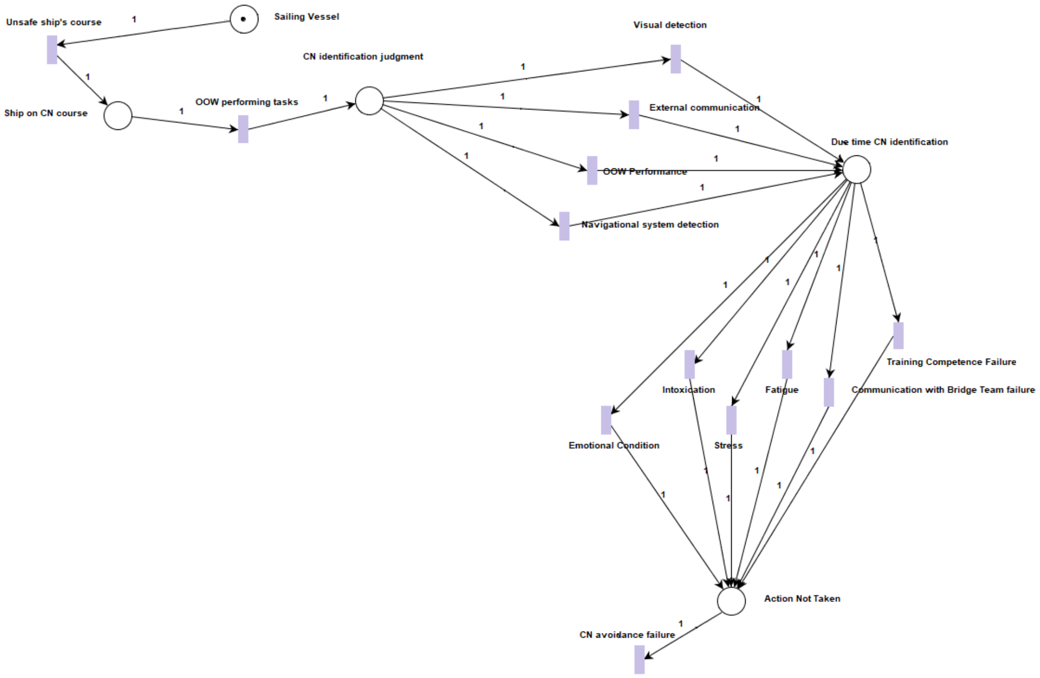


Figure 7.9: The probabilities which form P_b.

c. The calculation of P_c

In Figure 7.10, the values of probabilities which should be considered in order to calculate P_c are highlighted with a light blue colour. The calculation of P_c is the following:

$$\begin{gathered}
P_c = P(t_1) \cdot P(t_2) \cdot P(t_7) \cdot P(t_{17}) \cdot P(t_{18}) \cdot P(t_{25}) + P(t_1) \cdot P(t_2) \cdot P(t_8) \cdot P(t_{17}) \cdot \\
\cdot P(t_{18}) \cdot P(t_{25}) + P(t_1) \cdot P(t_2) \cdot P(t_9) \cdot P(t_{17}) \cdot P(t_{18}) \cdot P(t_{25}) + P(t_1) \cdot \\
\cdot P(t_2) \cdot P(t_{10}) \cdot P(t_{17}) \cdot P(t_{18}) \cdot P(t_{25}) + P(t_1) \cdot P(t_2) \cdot P(t_7) \cdot P(t_{17}) \cdot \\
\cdot P(t_{19}) \cdot P(t_{25}) + P(t_1) \cdot P(t_2) \cdot P(t_8) \cdot P(t_{17}) \cdot P(t_{19}) \cdot P(t_{25}) + \cdots + \\
+P(t_1) \cdot P(t_2) \cdot P(t_{10}) \cdot P(t_{17}) \cdot P(t_{22}) \cdot P(t_{25}) \\
P_c = P(t_1) \cdot P(t_2) \cdot P(t_{17}) \cdot P(t_{25}) \cdot \big(P(t_7) + P(t_8) + P(t_9) + P(t_{10})\big) \cdot \\
\cdot (P(t_{18}) + P(t_{19}) + P(t_{20}) + P(t_{21}) + P(t_{22}))
\end{gathered}$$

The probability value of the transition t_{21} is differentiated, regarding the three encounter scenarios.

- Head-on scenario ($P(t_{21})=0.2$),

$$\begin{gathered}
P_{c(head\_on)} = 0.001 \cdot 0.99 \cdot 0.996 \cdot 0.762 \cdot (0.86 + 0.3 + 0.925 + 0.968) \cdot \\
\cdot (0.0001092 + 0.001 + 0.33 + 0.2 + 0.004)
\end{gathered}$$

$$P_{c(head\_on)} = 0.00122749$$

$$P_{c(head\_on)} = 0.0012$$

- Crossing scenario ($P(t_{21})=0.58$),

$$\begin{gathered}
P_{c(crossing)} = 0.001 \cdot 0.99 \cdot 0.996 \cdot 0.762 \cdot (0.86 + 0.3 + 0.925 + 0.968) \cdot \\
\cdot (0.0001092 + 0.001 + 0.33 + 0.58 + 0.004)
\end{gathered}$$

$$P_{c(crossing)} = 0.0020991778$$

$$\mathrm{P}_{\mathrm{c(crossing)}} = 0.0021$$

- Overtaking scenario ($P(t_{21})=0.22$),

$$\mathrm{P}_{\mathrm{c(overtaking)}} = 0.001 \cdot 0.99 \cdot 0.996 \cdot 0.762 \cdot (0.86 + 0.3 + 0.925 + 0.968) \cdot$$

$$\cdot\, (0.0001092 + 0.001 + 0.33 + 0.22 + 0.004)$$

$$\mathrm{P}_{\mathrm{c(overtaking)}} = 0.00127337$$

$$\mathrm{P}_{\mathrm{c(overtaking)}} = 0.0013$$

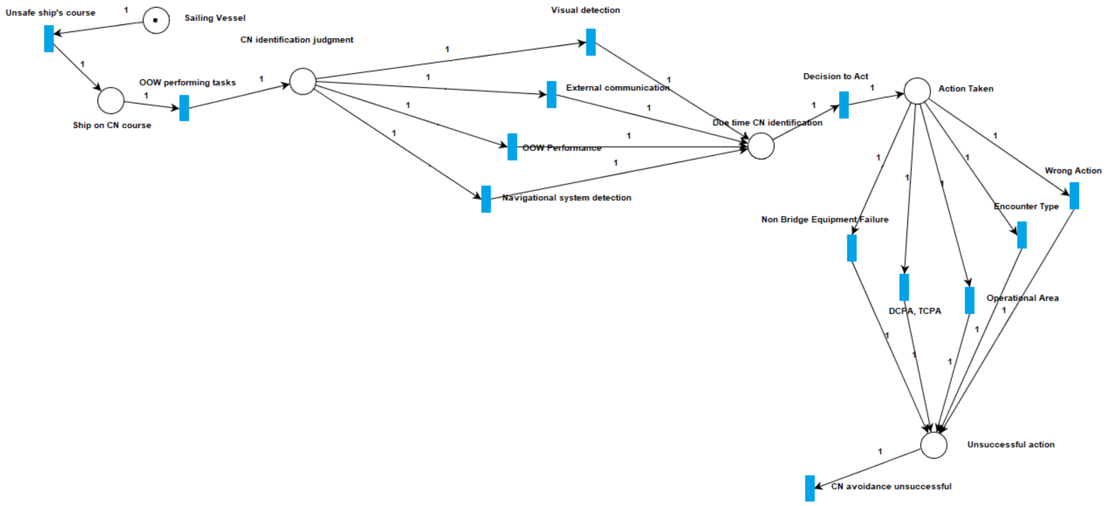


Figure 7.10: The probabilities which form P_c.

After the calculation of the probabilities P_a, P_b and P_c, the calculation of the probability P_1 is achievable. At this point, it is worth noting that the probability P_1 is the probability which concerns only our vessel as responsible for the collision accident. However, in the developed PN model, both ships are taken into account. In Figure 7.11, the place of the probability P_1 is coloured in pink and the three probabilities P_a, P_b and P_c are coloured in green. According to the probability calculation that is presented in the paper of Philippi et al., P_1 is equal to:

$$\mathrm{P}_1 = \sum \mathrm{P}_\mathrm{i}\,, \qquad \mathrm{i} = \mathrm{a, b, c}$$

$$P_1 = P_a + P_b + P_c$$

- Head-on scenario

$$P_{1(head\_on)} = 7.8190E - 04 + 0.0018 + 0.0012$$

$$P_{1(head\_on)} = 0.0037819$$

$$P_{1(head\_on)} = 0.0038$$

- Crossing scenario

$$P_{1(crossing)} = 7.8190E - 04 + 0.0018 + 0.0021$$

$$P_{1(crossing)} = 0.0046819$$

$$P_{1(crossing)} = 0.0047$$

- Overtaking scenario

$$P_{1(overtaking)} = 7.8190E - 04 + 0.0018 + 0.0013$$

$$P_{1(overtaking)} = 0.0038819$$

$$P_{1(overtaking)} = 0.0039$$

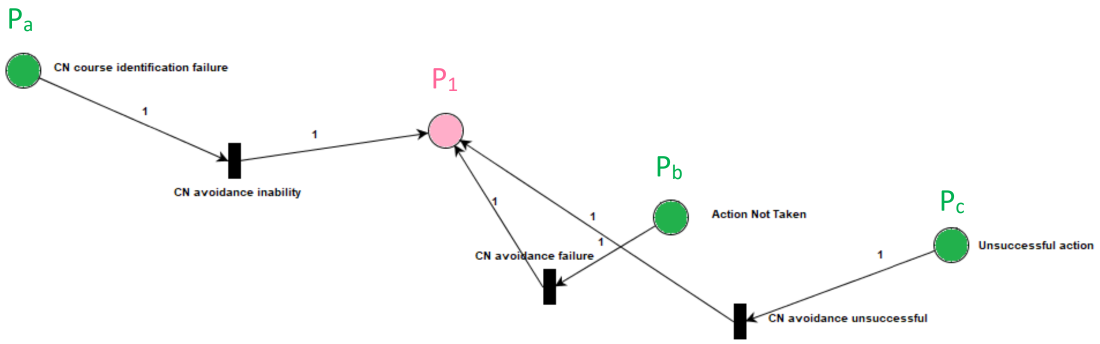


Figure 7.11: The probabilities which form the theoretical probability P_1.

As it has been already highlighted above,

$$P_{collision} = f(P_1, P_2) \text{ and}$$

$$P_1 = P_2$$

Thus, P_2 ($P(t_{26})$) is equal to

- Head-on scenario

$$P_{2(head\_on)} = 0.0038$$

- Crossing scenario

$$P_{2(crossing)} = 0.0047$$

- Overtaking scenario

$$P_{2(overtaking)} = 0.0039$$

According to Figure 7.7, the definition of the probabilities P_a, P_b, P_c, the sum of which compose the probability P_1, P_2 and the probability calculation which is presented in the paper of Philippi et al.,

$$P_{collision} = P(t_{27})$$

$$P_{collision} = P_1 \cdot P_2$$

$$P_{collision} = {P_1}^2$$

- Head-on scenario

$$P_{collision(head\_on)} = 0.0038^2$$

$$P_{collision(head\_on)} = 0.00001444$$

$$P_{collision(head\_on)} = 1.44E - 05$$

- Crossing scenario

$$P_{collision(crossing)} = 0.0047^2$$

$$P_{collision(crossing)} = 0.00002209$$

$$P_{collision(crossing)} = 2.21E - 05$$

- Overtaking scenario

$$P_{collision(overtaking)} = 0.0039$$

$$P_{collision(overtaking)} = 0.00001521$$

$$\mathrm{P}_{\mathrm{collision(overtaking)}} = 1.52\mathrm{E} - 05$$

In the tables that follow (Table 7.6 and Table 7.7) the probabilities of the transitions t_{26} and t_{27} are presented, regarding the encounter scenario.

Table 7.6: The probability values of the transition t_{26} (“Ship 2 fails to avoid CN”), regarding the encounter scenario.

Transition	t_{26}		
	Head-on	Crossing	Overtaking
Probability	0.0038	0.0047	0.0039

Table 7.7: The probability values of the required transition t_{27} (“Collision”), regarding the encounter scenario.

Transition	t_{27}		
	Head-on	Crossing	Overtaking
Probability	1.44E-05	2.21E-05	1.52E-05

8. Conclusions

8.1. General Literature

In this section, general conclusions and comments, which concern the existing literature, will be listed.

Based on the PN model which was developed in the context of the present thesis, collision probability calculation was made and the results are gathered in Table 7.7. At this point, it is worth comparing the results with other, previous results of the existing literature. In Table 8.1, the collision probability that has been calculated through numerous studies is presented.

In the paper of Mulyadi et al., the collision probability is acquired for the case of collision between vessels that sail in the Madura Strait. The order of magnitute is lower, in comparison with the results of the current developed PN model. However, the probability that is calculated in the present thesis considers a generalised collision scenario, which is not focused on the vessel's operating area. Thus, a probability that concerns the collision materalisation in an area where shallow waters and dangerous sea locations exist (see Figure 8.1), logically receives a greater value.

In the paper of Sotiralis et al., the collision probability which is calculated regards the crossing encounter situation. The order of magnitude is the same, compared to the results of the current developed PN model. Both the work of Sotiralis et al. and the present thesis study a generalised collision model and thus, the acquired results are justifiably similar.

In the FSA of Det Norske Veritas, the probability of ship collision is acquired, for the case of cruise vessels. The order of magnitute is higher, in comparison with the results of the current developed PN model. However, the probability that is calculated in the present thesis considers a generalised collision scenario, which is not focused on the type of the sailing ship. Cruise ships are considered a special type of vessel, as, on the one hand, the cruise ship personel is highly trained and on the other hand, special safety rules are applied to the specific type of ship. Thus, logically the collision probability of cruise ships receives a lower value.

In Table 8.2, values of the collision probability that consider the encounter situation are presented. The aforementioned values are calculated in the paper of Przywarty et al. and are acquired for the case of collision between a passenger vessel and a tanker, which might happen in the waters of the Baltic Sea. Compared to the results that derived from the present analysis, the probability values of Przywarty et al., which as well regard the encounter type, are similar and of the same order of magnitude.

However, Kim et al. have concluded to collision probability values which differ in the order of magnitude, compared to the corresponding results of the present thesis. The study of Kim et al. is conducted for the geographical area of Mokpo Port in Korea, which is a narrow waterway of 620 meters width and 30 meters depth (Mokpo Regional Office of Oceans and Fisheries, 2013), thus being a very tough location for vessel traffic. The collision probability of the present thesis is not focused on the vessel's operational area, which means that, as a generalised value, it is logically lower than a corresponding probability which studies the potential collision in a limited waters area.

Table 8.1: The ship collision probability, according to sources of the existing literature.

CN Probability Value	Source
1.08E-04	(Mulyadi et al., 2014)
2.1E-05	(Sotiralis et al., 2016)
8.6E-06	(Det Norske Veritas Maritime Solutions Limited, 2002)

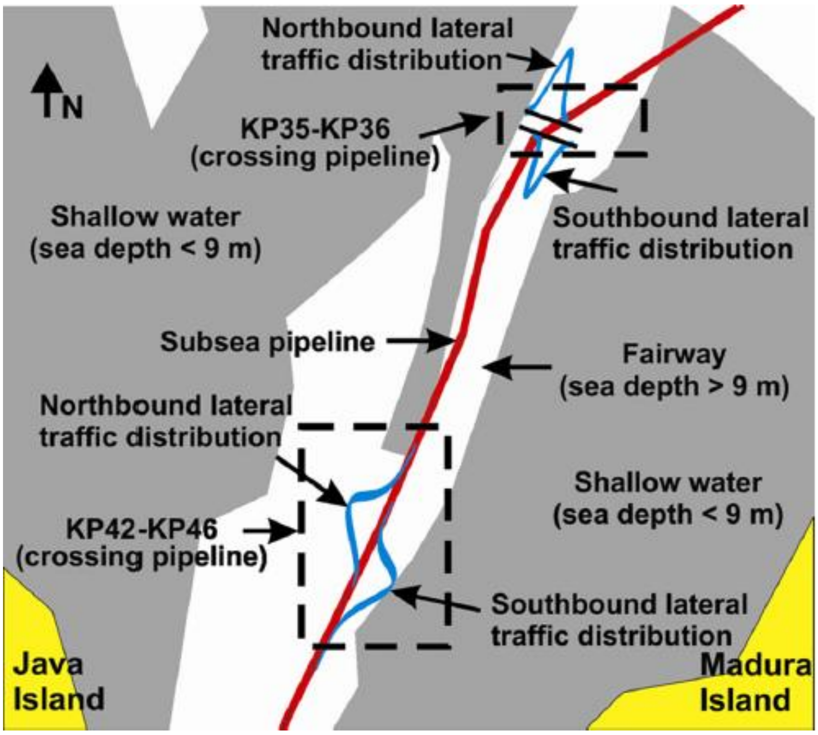


Figure 8.1: The dangerous locations beneath the surface of the Madura Strait sea (Mulyadi et al., 2014).

Table 8.2: The probability of vessel collision, considering the different possible encounter situations, according to the existing literature.

Encounter Type	CN Probability Value	
Head-on	4.96E-05	0.5E-04
Crossing	5.6E-05	1.1E-04
Overtaking	3.98E-05	1.3E-04
Source	(Przywarty et al., 2015)	(Kim et al., 2011)

According to the collision probability results that derived from the international literature, the obtained probability calculation of the present thesis seems to present some similarities and some differences. However, the differences of the acquired results are justifiable, as each analysis was made considering different facts and focusing on different collision characteristics (geographical area, ship type, etc.). Similarly conducted studies led to similar results.

For the sake of completeness, in Table 8.3, vessel collision frequency values are listed, according to sources that exist in the international literature. The aforementioned probabilities are acquired regarding the type of vessel.

Table 8.3: The ship collision frequency, according to sources of the existing literature.

Vessel Type	Collision Frequency	Source
Large Passenger Ships	2.80E-03	(Det Norske Veritas Maritime Solutions Limited, 2002)
Cruise Ships	6.36E-03	(European Maritime Safety Agency, 2014)
Tankers	6.70E-03	(Vanem et al., 2007)
Bulk Carriers	2.60E-03	(Skjong and Vanem, 2004)
Containerships	1.61E-02	(Ellis et al., 2008)

8.2. Suggestions for Future Work

According to the international literature, the collision probability results that were obtained are quite satisfactory. However, the collision probability value would be more accurate, if, on the one hand, specific collision scenarios were studied (eg. considering the ship type and size, the operational area etc.) and, on the other hand, if more leading factors for vessel collision occurrence were considered (weather conditions, sea currents, age of the seafarers, flag of the vessel etc.). An interesting attempt would be the time factor addition to the PN model, thus obtaining more realistic results. As it is easily understood, however, the time addition would probably presuppose simulation experiments.

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