ADVANCED DECISION SUPPORT SYSTEM FOR SHIP DESIGN, OPERATION AND TRAINING (ADOPT)

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Summary:

This document:
- is the Publishable Final Activity Report of the ADOPT project
- summarises the results of ADOPT and identifies potential areas where further development might be needed

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Table of Contents

1. SUMMARY 1

1.1. OBJECTIVES OF ADOPT 2

2. INTRODUCTION 4

2.1. BACKGROUND 4
2.2. APPROACH 7
2.3. RESULTS 9
2.3.1. Mode 3 - Design 10
2.3.2. Mode 2 - Training 14
2.3.3. Mode 1 – Operation 16
2.4. IMPLEMENTATION CONCEPT 18

3. OCEAN ENVIRONMENT MODELLING FOR USE IN ADOPT DSS 21

3.1. INTRODUCTION 21
3.2. HINDCAST DATA FOR DESIGN AND TRAINING MODE 22
3.2.1. The wave model 22
3.2.2. Wave model results 23
3.3. REAL TIME MEASUREMENTS FOR OPERATION MODE 25
3.3.1. Quality control 26
3.3.2. Wind measurements 27
3.4. COMBINATION OF DATA FOR THE NUMERICAL SURFACE ANALYZER 29
3.4.1. Input Type 1 30
3.4.2. Input Type 2 31
3.5. CREATING IRREGULAR SEAWAYS FOR NUMERICAL MOTION SIMULATIONS FROM DIRECTIONAL SPECTRA 31
3.6. CONCLUSIONS AND NEEDS FOR FURTHER DEVELOPMENT 33

4. THE PROBABILISTIC METHOD WITHIN A RISK ASSESSMENT FRAMEWORK 34

4.1.1. The Probabilistic Core of a Decision Support System 34
4.1.2. Low Probability Events 35
4.1.3. Hazards Identification 36
4.1.4. Threshold Values 36
4.1.5. Environmental conditions 36
4.1.6. Hazards formulation 37
4.1.7. Ship Motion Model 37
4.1.8. Uncertainties 38
4.1.9. Seakeeping events 39
4.2. THE PROBABILISTIC ASSESSMENT 40
4.2.1. Monte Carlo Simulations 40
4.2.2. Reliability Methods 41

5. NUMERICAL SIMULATION – FREQUENCY DOMAIN IMPLEMENTATION 44

5.1. INTRODUCTION 44
5.2. IMPLEMENTATION 44
5.2.1. Seakeeping Code 44
5.2.2. Probabilistic Program 45
5.2.3. Probabilistic Module 45
5.2.4. Computational Performance 46
5.2.5. DSS Modes 46
5.3. CONCLUSIONS 47
5.4. NEEDS FOR FURTHER DEVELOPMENT 47

6. NUMERICAL SIMULATION – TIME DOMAIN IMPLEMENTATION 49

6.1. INTRODUCTION 49

6.2. E4- ROLLS SIMULATION TOOL 51
6.3. FAILURE CRITERIA 52
6.3.1. General 52
6.3.2. Soeding's Concept of Simulating Rare Events by Artificially Amplified Wave Heights: 52
6.3.3. The Blume Criterion of the residual area 53
6.3.4. The Insufficient Stability Event Index (ISEI) 54
6.4. APPLICATION EXAMPLE: THE FINNBIRCH ACCIDENT 59
6.4.1. Background of the Accident 59
6.4.2. Validation of the ADOPT DSS operational mode, Mode 1 60
6.4.3. Validation of the ADOPT DSS training mode, Mode 2 61
6.4.4. Validation of the ADOPT DSS design mode, Mode 3 62
6.5. CONCLUSIONS AND NEEDS FOR FURTHER DEVELOPMENT 62

7. MAN-MACHINE INTERFACE 63

7.1. INTRODUCTION 63
7.2. GENERIC LAYOUT OF THE MAN-MACHINE-INTERFACE 63
7.2.1. Structure of the Man-Machine-Interface 63
7.2.2. Data Presentation 65
7.3. INTEGRATION OF ADOPT MMI INTO NAVIGATION SYSTEM 67
7.3.1. Bridge Overview 67
7.3.2. Conning Pilot 68
7.3.3. Chart Pilot 69
7.4. ADOPT USER INTERFACE DESIGN RULES 69
7.5. ADOPT USER INTERFACE IMPLEMENTATION 70
7.6. CONCLUSIONS AND NEEDS FOR FURTHER DEVELOPMENT 72

8. TRAINING 74

8.1. INTRODUCTION 74
8.2. TRAINING COURSE OUTLINE AND TEACHING SYLLABUS 75
8.2.1. Theory of ship motions 75
8.2.2. Characteristics and behaviour of specific ship 76
8.2.3. Familiarization with ADOPT DSS (Mode 1) 76
8.3. CONCLUSIONS AND NEEDS FOR FURTHER DEVELOPMENT 77

9. OVERALL CONCLUSIONS AND OUTLOOK 78

10. DISSEMINATION AND USE 80

11. ACKNOWLEDGEMENTS 82

12. REFERENCES 83

13. LIST OF ADOPT DELIVERABLES 87

List of Tables

Table 2-1: Warning dilemma (Courtesy of Arne Braathens, DNV) 4
Table 2-2: ADOPT High level requirements 8
Table 2-3: ADOPT components, implementation in the three modes 20
Table 3-1: Integrated parameters included in the final wave data set 23
Table 3-2 : Statistics for the time period 1990/10/01-1991/01/01, 00 UTC at K-13 (H_S) 24
Table 3-3: Accuracies for wave model and WaMoS II data 31
Table 7-1: Comparison of Risk Polar Plot, Radar, ECDIS and 3D wave spectrum 66

List of Figures

Figure 1-1 Objectives of ADOPT and modes that constitute the DSS 3
Figure 2-1: Example of a polar plot. Loading condition, wave length, failure criterion, and threshold fixed 5
Figure 2-2: ADOPT high level system structure and work structure 6
Figure 2-3: ADOPT Process 7
Figure 2-4 : Calibration of ADOPT system in mode 3 10
Figure 2-5: ADOPT Modules and data sets, for design and operation 19
Figure 3-1 : Depth distribution for the ADOPT North Sea wave model grid in metres. 22
Figure 3-2 : Distribution of significant wave height in the North Sea on 1990-02-28, 00 UTC 24
Figure 3-3 : Time series of measured and computed wave data at the location K-13 25
Figure 3-4 : Analysis areas of WaMoS II for Tor Magnolia (2005-12-15 at 10:03 UTC). 26
Figure 3-5 : Result of quality control marked in time series of sea state parameters.............27
Figure 3-6 : Scatter diagram: Mean Grey value and wind speed. 28
Figure 3-7 : Derived wind speed compared to reference 29
Figure 3-8 : Flowchart of the environmental data input into the DSS 30
Figure 3-9: Bi-modal directional wave spectrum 32
Figure 3-10: Time series of wave elevation amidships..33
Figure 4-1 The probabilistic module within the risk assessment framework 35
Figure 4-2 Distribution of the out-crossing rate of the vow vertical acceleration due to uncertainty on T_p 39
Figure 4-3 Distribution of bow slamming rate, due to uncertainty on H_s and T_p.....................39
Figure 4-4 Monte Carlo simulations for low probability events of bow vertical acceleration..40
Figure 4-5 2D *g*-function approach with FORM 42
Figure 4-6 *U*-space for H_s and T_p in operational mode...42
Figure 4-7 Probability of the vertical bow acceleration..43
Figure 5-1 The structure of the probabilistic module in operational mode 45
Figure 5-2 Probability for propeller emergence rate > (1 / min)..46
Figure 6-1: Example of a time series obtained with E4-ROLLS for a capsizing incident of a small coaster. 52
Figure 6-2: Concept of the Blume- Criterion related to the residual area under the still water righting lever curve from a maximum roll angle obtained during a model test until the point of vanishing stability...53
Figure 6-3 : Example of a polar diagram computed with E4-ROLLS for the limiting significant wave heights for a given significant period T1 which fulfill the Blume Criterion. The radial axis denotes the ship speed, the circumferential axis the encounter angle. Left: A typical RoRo-ferry with pronounced 2:1 and 1.1 resonances in following seas. Right: Improved design by modified hull form and stability as risk control option. 54
Figure 6-4: ISEI- values computed for different ships including some real full scale stability accidents. 57
Figure 6-5: Accident scenario (left) and the final floating condition of the MV FINNBIRCH after the accident. 59
Figure 6-6 Righting levers of MV FINNBIRCH during the accident for Stillwater, crest and trough (left) and time series obtained from the E4ROLLS implementation. Note that during the simulation, the vessel easily reaches roll angles beyond 40 degree in the accident situation, because the stability on the wave crest is insufficient. 60
Figure 6-7 : Polar Diagrams with limiting significant wave heights according to the Blume Criterion during the simulated ADOPT DSS training environment. The limiting significant

wave heights were computed for different significant wave lengths from 88 to 172 m. The accident wave length was about 113 m. 61
Figure 7-1: Overview of the MMI structure 64
Figure 7-2: Presentations of the overall risk 65
Figure 7-3: Presentation of the risk in all limit states 67
Figure 7-4: Bridge Layout for Ro-Ro Vessel 68
Figure 7-5 Conning Layout, daylight 68
Figure 7-6: Chart System (ECDIS) 69
Figure 7-7: ADOPT Limit State Presentation 70
Figure 7-8: Wave Indicator 71
Figure 7-9: ADOPT Polar Plot 72

1. Summary

The present report summarizes the results achieved during the 3½ year ADOPT project (Advanced Decision Support System for Ship Design, Operation and Training). A STREP project funded by the European Community under the 6th Framework Programme Sustainable Surface Transport Programme, Contract No. FP6-TST4-CT-2005-516359. and performed by the partners:

- **Flensburger Schiffbau-Gesellschaft mbH & Co. KG (Project coordinator) (DE)**
- **GKSS-Research Centre, Institute for Coastal Research / System Analysis and Modelling (DE)**
- **OceanWaveS GmbH (DE)**
- **Force Technology (DK)**
- **Technical University of Denmark, Department of Mechanical Engineering, (DK)**
- **DFDS A/S (DK)**
- **Hamburg University of Technology - Institute of Ship Design and Ship Safety (DE)**
- **National Technical University of Athens – Ship Design Laboratory (GR)**
- **Technical University of Hamburg-Harburg – Maritime Logistics ISSUS (DE)**
- **SAM Electronics GmbH (DE)**
- **Uniresearch BV (NL)**

ADOPT aims at developing a concept for a risk-based, ship specific, real-time Decision Support System (DSS) covering three distinct modes of use:

- Design,
- Training,
- Operation.

The number one priority of the ADOPT-DSS is to assist the master to identify and avoid potentially dangerous situations.

The ADOPT-DSS is an integration of the three modes design, training, and operation and will be customized for a specific ship and aims at utilizing state-of-the-art know-how and technology not available widely today.

The basis is the design (or office) mode. Information generated in the design mode is passed on to the training mode. Training can be provided directly using the information generated in design mode. In addition, the master can be trained for using the operation mode implementation of the ADOPT-DSS. One of the challenges in the ADOPT project in developing such a system has been to interface and connect various data sources, hardware, and software systems, that might run on various IT platforms.

1.1. Objectives of ADOPT

The present document summarises the results achieved in ADOPT and thereby verifies fulfilment of the overall objectives of ADOPT.

The objectives of ADOPT from Annex I to the Contract were:

- *"to develop a reliable system for the bridge that senses the actual environment, joins the available information, takes into account 'new' phenomena and calculates the consequences (…) of all possible navigational changes thereby supporting the captain and his crew in decision making."*

- *„Creating a reliable system that will assist the captain in deciding safe and efficient ship handling, based on the sum of the actual sensed environmental situation, the ship's condition, the ship's behaviour, the expected sea state on all alternative courses, the prediction of ship motions on all these courses caused by the prevailing conditions, etc.*
  In other words: sensing the environment, predicting the ship's responsive motions and supplying the captain with information on suitable Risk Control Options.
  This system will be designed for use in operation and in training, but also in design, supporting the naval architect with information on how the ship will perform in real life. In crew training simulating the different expected conditions and training the crew to take decisions based on actual data, will help them to better understand the ship's behaviour even without the DSS and to take the appropriate Risk/lControl Option."

- *The system is intended to be used in design*
  "By being able to simulate actual and relevant situations during ship design, the actual use of the ship can be predicted and the design being altered according to the needs during operation, leading to ships exceeding the safety level inherent in current rules and regulations in a very cost effective way (actual costs are close to zero, potential benefit in the M€ region) while delivering more performance (less cargo damage, less lashing, more passenger comfort)."

- *In training*
  „In order to raise safety at sea, crews must be well prepared with what is to be expected and how can that be mitigated. By creating sound simulation conditions they will gain experience on shore that will have a tremendous impact on the safe and efficient operation of modern ship types."

- *And in operation*
  "By being able to predict a ship's response at specific operating and environmental situations, the ship's performance in arbitrary conditions can be significantly improved. This is favourable in moderate to rough conditions for lashing requirements, fuel consumption and (passenger) comfort. In rough to severe conditions the system will reduce significantly the number of accidents, by being able to accurate predict the risk in actual critical situations and to assess appropriate Risk Control Options."

The main objectives relate to modes of use as shown in Figure 1-1 below. The numbers in the cells do not prioritize, they are identifier for the cells. In particular for operation it is important to realize, that „reliable risk-based support in real-time“ does not necessarily mean that advanced numerical and statistical computations are performed on a bridge in real-time, but that advice is given in real-time, the basis for this advice is risk-based, and the advice as such is reliable.

Figure 1-1 Objectives of ADOPT and modes that constitute the DSS

Objective	DSS mode of use		
	Operation	Training	Ship Design
Reliable risk-based support in real time	*Main objective 1*		
Prepare crew, create sound simulation conditions		*Main objective 2*	
Design safer/more efficient ships			*Main objective 3*

WP0, Review of Objectives, Jan Tellkamp 10

2. Introduction

ADOPT aims at developing a concept for a risk-based, ship specific, real-time Decision Support System (DSS) covering three distinct modes of use: Design, Training, Operation. The number one priority of the ADOPT-DSS is to assist the master to identify and avoid potentially dangerous situations. The ADOPT-DSS will be customized for a specific ship and aims at utilizing state-of-the-art know-how and technology not available widely today. Therefore, the three modes are building upon each other. The basis is the design (or office) mode. Information generated in the design mode is passed on to the training mode. Training can be provided directly using the information generated in design mode. In addition, the master can be trained for using the operation mode implementation of the ADOPT-DSS. The challenge in developing such a system is to interface and connect various data sources, hardware, and software systems, that might run on various IT platforms.

2.1. Background

Ship accidents or near misses due to heavy seas are reported frequently, e.g. *Kernchen (2008)*, *McDaniel (2008)*. Apart from these safety related accidents, damages non-critical from a safety perspective occur even more frequently. These damages are of high economic concern, as their impact span from on-board repair to taking vessels out of service for docking. In the latter case, economic consequences are in the order of magnitude of 100,000 Euro. IMO MSC/Circ. 707, *IMO (1995)*, gives guidance to masters in the form of simple rules for identification of potentially harmful situations. There are also computer systems that aim at improving the situation.

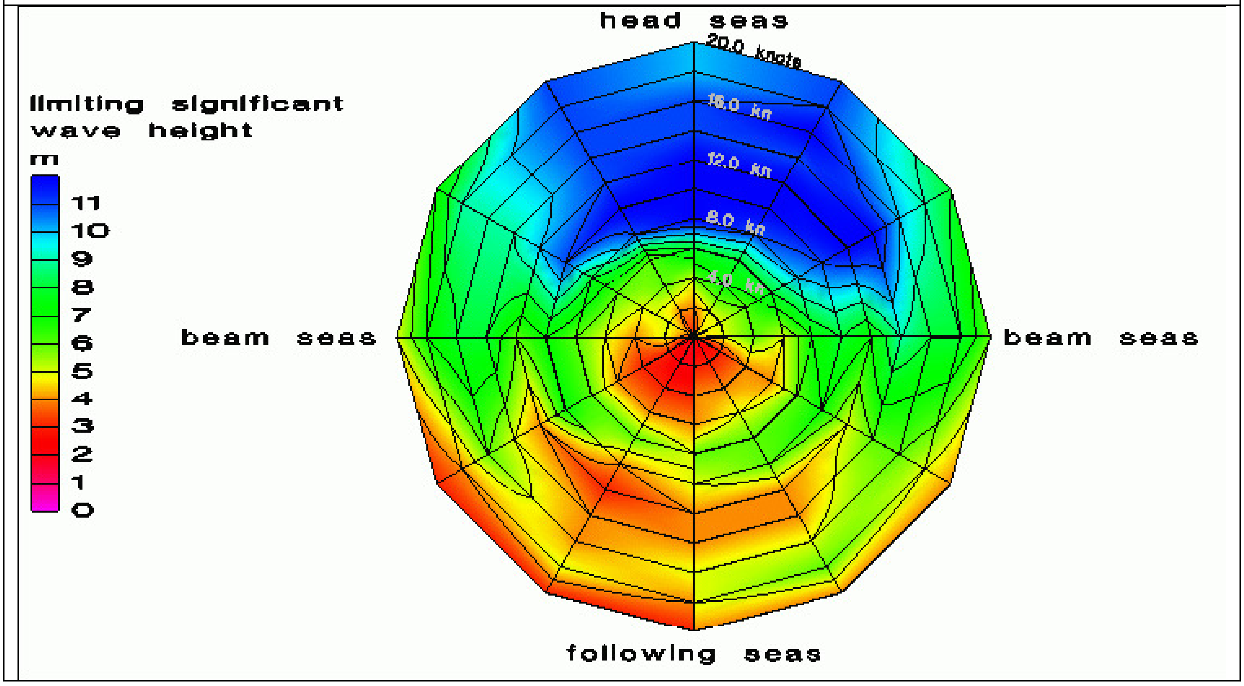
All support on the bridge is subject to the *Warning Dilemma*. The warning dilemma as presented in Table 2-1 depicts a high level requirement on any system, that aims at giving warning in critical situations. Core of the warning dilemma is, that safety critical systems shall issue warnings only, if action is required, but always, if action is required. Warning that are issued, if no action is required might increase the risk. Warnings that are not issued if action is required, might have two reasons – either the system is not capable in assessing a situation, or it has a malfunctions. If either of these combinations occur during operation, the confidence of the user in the system is degraded.

	Action required	Action not required
Warning issued	OK	not OK
Warning not issued	not OK	OK

Table 2-1: Warning dilemma (Courtesy of Arne Braathens, DNV)

On the other hand, during the design phase of a ship a massive amount of numeric simulations are carried out using direct calculation tools. Basis for these calculations are the ship in its current design stage, the operational envelope of the intended service, and environmental data. As one result of these investigations, limits of the operational envelope are determined, or the design is altered. If limits are determined, one way of presenting them are polar diagrams, giving limiting significant wave heights as a function of encounter angle and ship speed. The parameters of the polar diagrams are the wave length, the loading condition, and the exceedance of a certain threshold value, that might be a particular roll angle, accelerations at a certain position of the vessel, stresses in the structure, or other. An example is given in figure 2-1.

Figure 2-1: Example of a polar plot. Loading condition, wave length, failure criterion, and threshold fixed



This example shows that in following seas at low speeds the vessel will exceed the set threshold value for the selected criterion already in small waves of about two to three metres significant waveheight. Today, diagrams like the one given in figure 2-1 are generated during ship design and are compiled into operational manual booklets. These booklets are made available to the crew as paperware.
The challenge is to make this information available to the crew by making best use of information, knowledge, and IT tools that are available today. The objective then is to:

Assist the master to identify and avoid potentially dangerous situations.

It is obvious to achieve this objective using state–of–the–art tools and techniques that are available today. These tools and techniques can be found in the fields of risk–based decision making, sensing and modelling the environment, numerical simulations, handling of ship data, and Man–Machine–Interfacing. The ADOPT project is structured in this fields, as shown in Figure 2-2.

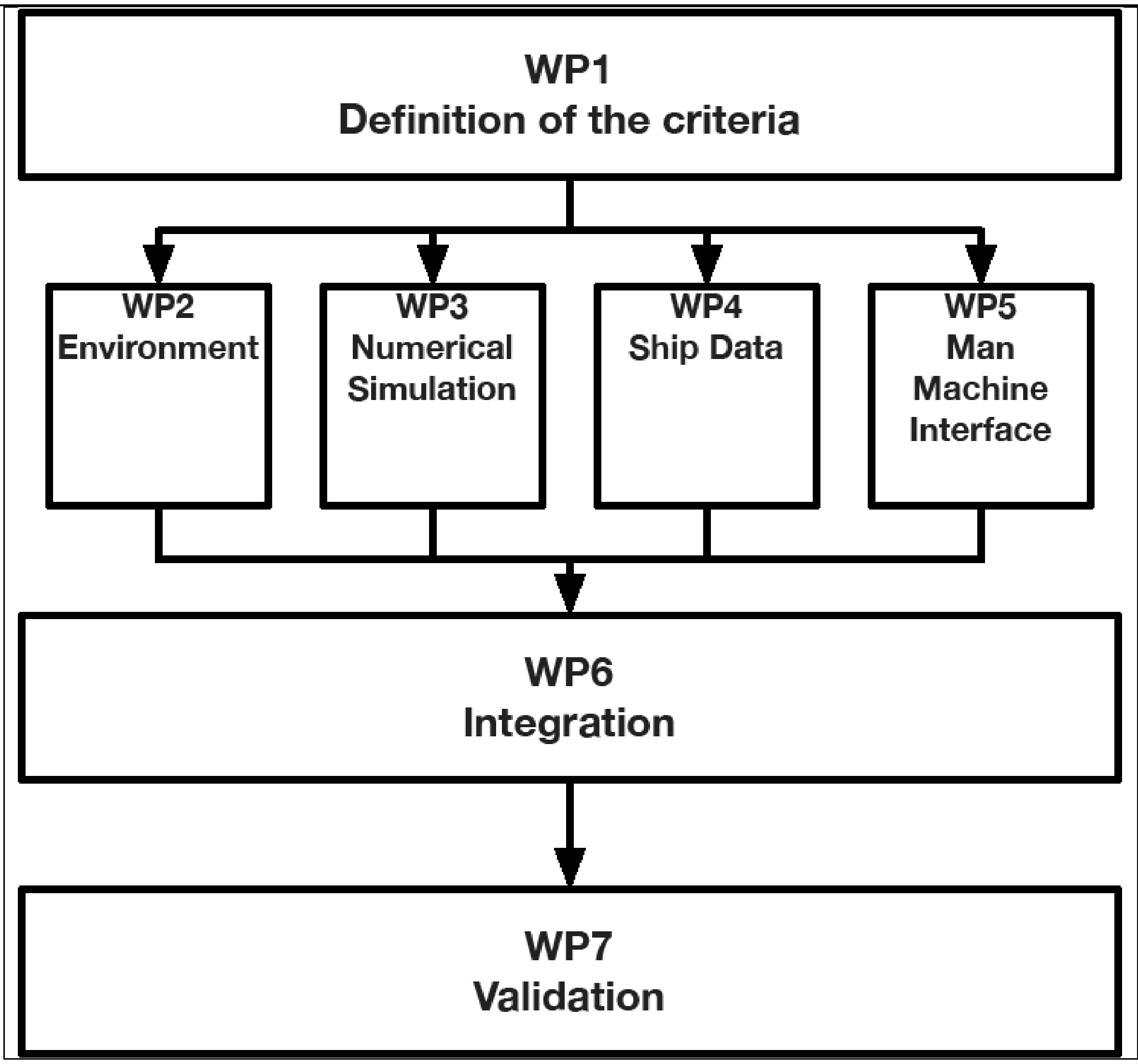
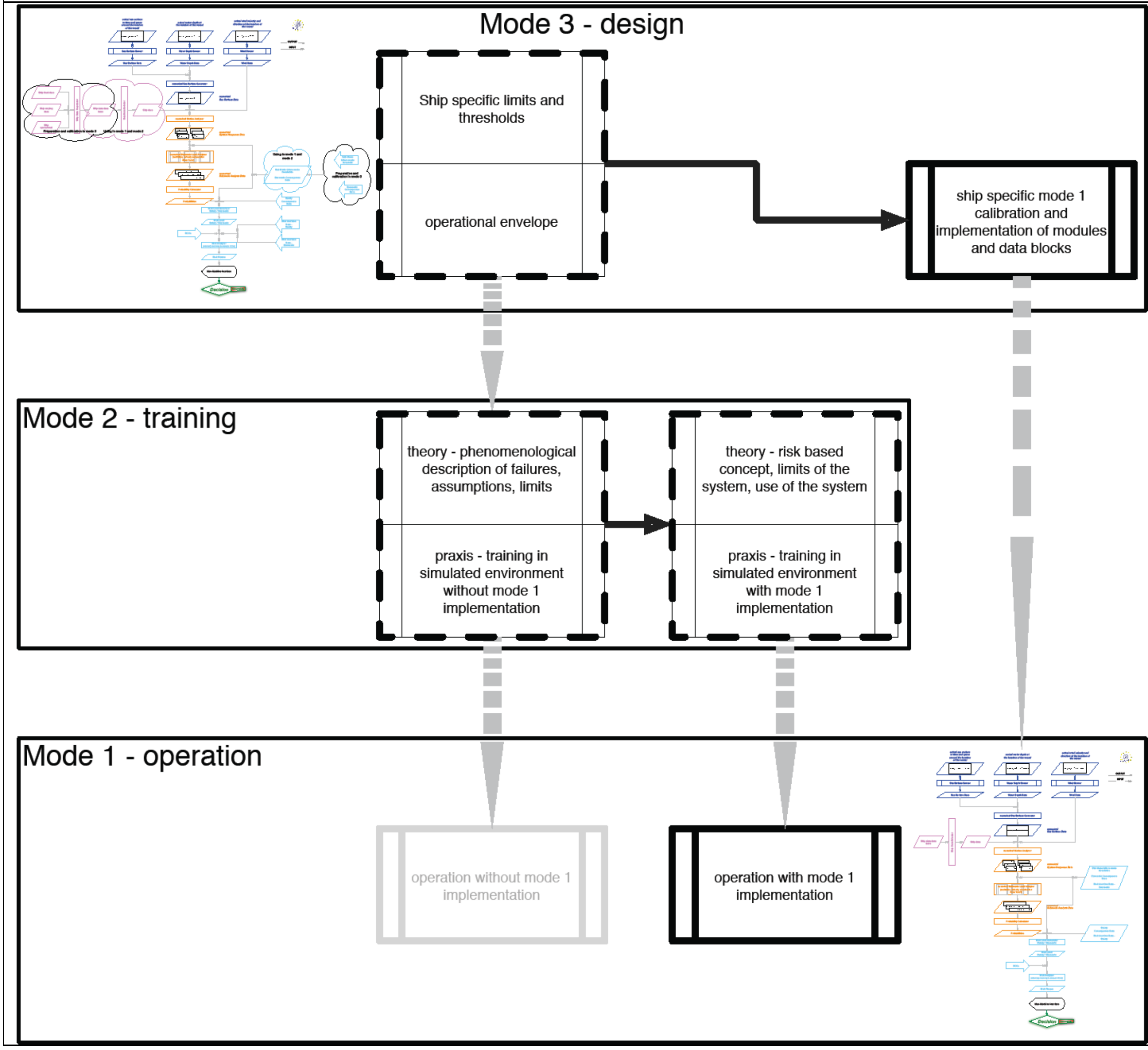


Figure 2-2: ADOPT high level system structure and work structure

The result of ADOPT is not only hardware and software which can be installed on the bridge of a ship. In order to satisfy the requirements as listed in Table 2-2, a process has been developed that covers ship design, training, and operation, see figure 2-3.

Figure 2-3: ADOPT Process



2.2. Approach

ADOPT has identified a number of high–level requirements on decision support systems. They are listed in Table 2-2. The requirements have been derived from a Hazard Identification Session, and by a number of interviews with captains. Additionally, requirements resulted from state of the art studies in the fields of environment, numerics, ship data, and Man-Machine Interface.

1 – The DSS shall be modular.
2 – The DSS shall be risk-based.
3 – The DSS shall support real-time decision making.
4 – Supported by a DSS, the master shall improve his decision making under uncertainty.
5 – The DSS shall take into account the relevant uncertainties from all sources.
6 – The DSS shall provide quality control regarding the reliability of the displayed information.
7 – Decision support shall have a time range of about one watch.
8 – The DSS shall operate on a ship while sailing.
9 – The DSS shall be operated and used by a ship's crew.
10 – The DSS shall take into account incomplete knowledge about mass distribution.
11 – The DSS shall take into account information overload.
12 – The DSS shall take into account lack of familiarization with the ship.
13 – The DSS shall take into account large accelerations.
14 – The DSS shall take into account lever arm alterations.
15 – The DSS shall take into account failure of or insufficient propulsion.
16 – The DSS shall take into account loss of structural integrity.
17 – The DSS shall take into account failure of rudder.
18 – The DSS shall take into account large roll motions, including sudden large roll motions.
19 – The DSS shall take into account extreme environmental conditions.
20 – The DSS shall take into account multiple wave systems.
21 – The DSS shall take into account damage to interior equipment.
22 – The DSS shall take into account threats to crew safety.
23 – The DSS shall take into account damage to equipment on deck.
24 – The DSS shall avoid misinterpretation of displayed information.
25 – The DSS shall avoid display of wrong information.
26 – The DSS shall be robust.
27 – The DSS shall avoid display of contradicting information.
28 – The DSS shall take into account inadequate use of the system.
29 – The DSS shall display information of limitations in the displayed content.
30 – The DSS shall take into account increased commercial pressure.
31 – The DSS shall take into account degraded personal experience.
32 – The DSS shall warn the user if risks arising from the identified hazards are beyond negligible.
33 – The DSS shall provide decision support, how to mitigate the situation if the risk is beyond negligible.
34 – The DSS shall be able to perform a self-assessment.
35 – The DSS shall handle performance criteria related to passenger and crew comfort and safety.
36 – The HMI shall be 'good'.
37 – The DSS shall be ship-specific.
38 – The DSS shall be reliable.

Table 2-2: ADOPT High level requirements

For assembling a system like the ADOPT system, expertise and subsystems are required from the fields of sensing of the environment, ship data handling, uncertainty modelling, motion simulation, probability calculation, and finally representation in a Man–Machine–Interface. These subsystems are either mature, or available as systems under development. On the other hand, these systems come from different manufacturers. Consequently, a modular approach has been chosen that identifies all relevant systems and data sets. This defines clearly interfaces and functionalities. With these interfaces and functionalities even a cross–platform implementation is possible. As well exchange of components due to the selection of other component suppliers, or an increase in knowledge is possible. Finally, the modularity of the system provides an implementation independent system definition.

Typical decision support systems provide at present decision support based on probabilities. This support has a core deficiency: If undesired events are assessed concurrently, it is not possible to decide what action to take. It is not obvious, whether a probability – or better frequency – of large roll angles of 10^{-7} per year is worse than a slamming frequency of 10^{-5}. Risk as a decision making concept is as well established at IMO, MARITIME SAFETY COMMITTEE, 2007. It is consequent to use the same principles for decision support on a ship, as they are used for developments at IMO level. For these reasons ADOPT uses risk as its decision metric.

The other key issue in ADOPT is the process view, that links design to operation via training.

2.3. Results

ADOPT provides a process with the three major process elements

- mode 3 – design,
- mode 2 – training and
- mode 1 – operation.

Decision support for mode 1 starts in mode 3. Mode 2 is required to convey the information generated in mode 3 to mode 1. Operation of a ship in mode 1 will be improved by mode 2 even without a specific computerized mode 1 DSS. A computerized mode 1 DSS will further improve the operation in mode 1 by giving real time support, which might capture scenarios beyond the experience or capabilities of the crew.

Figure 2-3 identifies the main steps in the process – mode 3, mode 2, and mode 1 – and the process elements within the modes that lead to the subsequent mode.

The upper box of Figure 2-3 represents the mode 3 – Design. The main elements are the identification of ship specific hazards with their limit states, and the identification of the operational envelope. Another task is the calibration and set-up of the ADOPT–DSS for the mode 1 use. Mode 3 links into both mode 2 – Training and mode 1 – Design. The function of the training is divided into two parts which corresponds to the two possible use of a DSS in the mode 1 – Operation, with and without a hard-/software implementation on board.

Figure 2-4 identifies the process elements within mode 3 that lead to specifically prepared data for use in mode 1, and specifically calibrated modules to be used in mode 1.

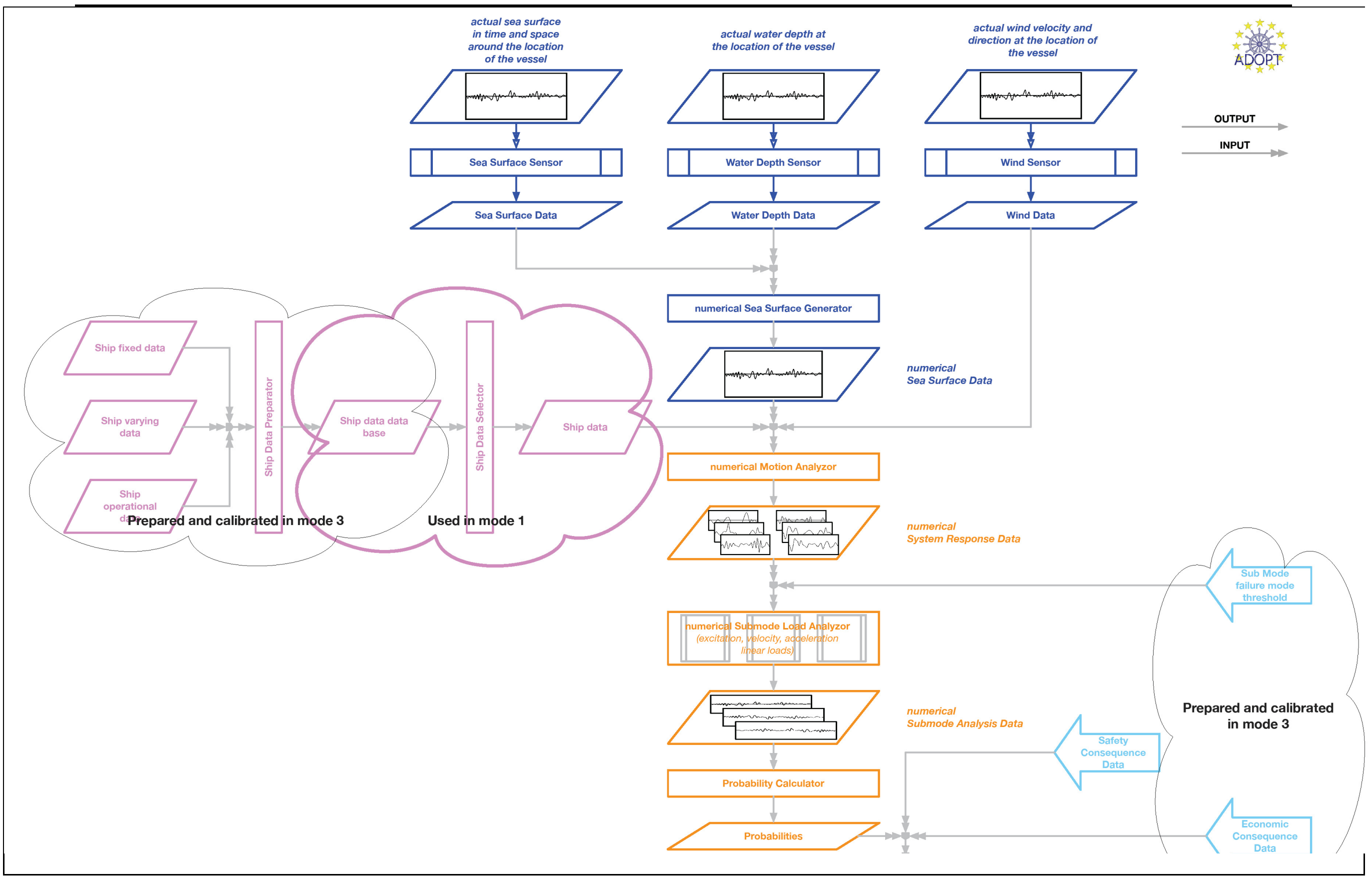


Figure 2-4 : Calibration of ADOPT system in mode 3

2.3.1. Mode 3 - Design

Of the list of requirements given in Table 2-2 the following requirements will be satisfied for the design mode (Mode 3):

- '1 – the DSS shall be modular',
- '2 – the DSS shall be risk-based',
- '5 – the DSS shall take into account the relevant uncertainties from all sources',
- '6 – the DSS shall provide quality control regarding the reliability of the displayed information',
- '29 – The DSS shall display information of limitations in the displayed content',
- '34 – The DSS shall be able to perform a self-assessment',
- '37 – The DSS shall be ship-specific',
- '38 – The DSS shall be reliable', and
- '39 – The DSS shall resolve internal contradictions and provide consistent decisions support'

The result of work carried out in mode 3 is an intimate understanding of the ships performance in critical situations. This knowledge can be made available to mode 1 by various means. Independently whether mode 1 is supported by a hard- and software implementation, a ship performance manual can be compiled. This manual describes the ship and the effect of selected Risk Control Options for the most critical scenarios. In addition, if a hard- and software implementation of the DSS is available to mode 1, the underlying data should be generated in mode 3. This ensures data consistency and process reliability.

Identification of operational envelope

The actual sea surface is represented by sea state data, that describes as well as possible the operational area of the vessel. Preferably, hindcast data is used here, as this gives consistent wind and wave data covering a wide range of conditions.
Based on the given environment and ship specific conditions, the added resistance in waves is calculated to determine the maximum speed possible in a seaway.
During an optimization process where the risk or frequency of a selected hazard is calculated the economical attractive solution may be to restrict the operational envelope. This is for example done by advising the master to avoid significant wave height over a certain level or recommend speed and heading combination in heavy sea. The processing of this recommendation(s) by the master requires proper training (mode 2).

Identification of ship specific hazards

The generic hazards identified so far in ADOPT and subject to implementation are:
1. Large amplitude roll motion (capsize).
2. Loss of lashed cargo.
3. Loss of not secured cargo (cars/trucks, container).
4. Shift of cargo / lashed RoRo cargo.
5. Shift of cargo / unsecured RoRo cargo (shift within cargo unit).
6. Large acceleration / injuries.
7. Large acceleration / reduced crew performance.
8. Green water (relative motion, damage to equipment/outfitting on deck).
9. Loss of course control.
10. Loss of propulsion.
11. Propeller racing (relative motion).
12. Wave bending moment.

A hazard identification is strongly recommended for each specific installation of a DSS.

Ship specific limit state formulation

According to its definition, a Limit State is *A state beyond which the structure no longer satisfies the requirements.* A Limit State Function is a *function of the basic variables, which is negative valued when the structural component fails, and which is positive valued when the structural component is safe, SKJONG (1996)*. This definition is extended to also including arbitrary ship properties or failure mechanism, like submergence of ventilation ducts, shift of cargo, slamming, deck wetness, or even ship capsize.

For the identified, ship specific limit states must be formulated. That is, the mathematical formulation of the phenomenon must be developed. In the easiest cases, analytical formulations e.g. taken from Class Rules might be taken. In such a case it is important to ensure that this formulation is adequate for the specific vessel.

Depending on the physics of a certain failure mode, the limit state formulation might involve complex simulations. In this case, the limit state formulation can be applied in design (mode 3) only. To be able to assess these type of failure in operation as well, a calibration of the limit state that allows for mode 1 assessment has to be performed. This calibration requires a limit state formulation that can be computed in mode 1, and a calibration of the respective failure threshold values.

An example is the combination of nonlinear simulation of ship motions, viscous CFD, and non linear FEM to calculate loads induced by slamming and the respective system response, that is the stresses within the steel structure. In mode 3, coupled fluid-structure-interaction will be used to assess certain scenarios. These results are used to calibrate a mode 1 implementation that is utilising relative motions and/or relative accelerations of ship and water.

Ship specific limit state threshold values

For the identified limit states, threshold values have to be determined. Using the above example of slamming, the deflections the steel structure can bear without failure is a ship specific threshold value. Dependent on the calculation procedure this corresponds to a hydrodynamic pressure on the ship's wetted surface which again is correlated to a relative velocity between water and hull at selected locations.

In the design process the equivalence between a structural based threshold value and ship motion based threshold as in the previous example may be developed for two purposes – optimization of the vessel with regard to the analyzed hazard and/or calibration for the mode 1 and 2. An optimization of a vessel with regard to a hazard implies a calculation of the risk or frequency of the ship specific hazard. During this step the desired correlation between the different thresholds are made. This equivalence can only be developed in mode 3, as mode 3 enables time for running necessary calculations and expertise for generation of math models and judging results of calculations.

The following example demonstrates the necessity of different limit state formulations and threshold classes for the same hazard dependent on the specific vessel. For the hazard 'Propeller Racing' the threshold value depends on the automation of the propulsion train and the main engine. If the automation enters shut–down–mode if the revolutions increase and the moment decreases, propeller emergence and duration of the emergence jointly establish the threshold value. If the automation does not shut down the main engine, but continuously adjusts engine revolutions and delivered power, the frequency of this process is the threshold value. Of course this is ship specific - if the automation is clever enough, the generic hazard: 'Propeller Racing' might not be that important for some implementation, except for perhaps very extreme operational conditions.

It is suggested to have escalating threshold values for each limit state. That means, the same hazard in its respective limit state formulation will have different consequences, if different threshold values are exceeded. For example, if the hazard is 'vertical accelerations leading to personnel injuries', one threshold value is pertinent to ship crew, another – most likely smaller – threshold value is pertinent to passengers.

Ship specific limit state and threshold value calibration for mode 1 use

Some limit state formulations and corresponding threshold values cannot be used in the DSS mode 1 implementation. Two reasons prohibit this: First, the required computation time for the respective calculations, and secondly the lack of expertise to judge the results.
As in mode 1 no advanced calculations, such as viscous CFD load generation, can be performed, some ship specific limit state formulations and respective threshold values have to be calibrated in mode 3 for being used in mode 1. The calibration consists of two steps; the development of physical and ship motion related models and the determination of the related threshold values.

Using slamming as an example, the exceedance of stresses in the steel structure will be associated with phenomena that are representative, but faster to compute in mode 1. For example characteristic relative velocities between critical points of the hull and the water could serve as a representative formulation. The threshold values for mode 3 use, the yield stress of the steel structure, is correlated to the threshold values for mode 1 use, relative impact velocity.

Identification of operator specific economic consequence data

The list of generic hazards given above has to be concretized and to be made both ship and operator specific. After this has been done it is necessary to assign a monetary consequence to the respective hazard. This gives the basis for the risk analysis that is carried out within the framework of an ADOPT–DSS.

For example, the hazard 'Shift of cargo / not secured Roro cargo (shift within cargo unit)' is made specific with the formulation *The contents of trailers on the leg Gothenburg – Immingham are shifted due to ship motions* as a first step.

The next step is to assign a monetary consequence to this event. A guideline for defining consequence is not to have the worst case scenario in mind, but to consider the 'worst credible consequence'.

In this example, a worst case might be damaging the content of a trailer containing time critical expensive goods, e.g. pharmaceuticals that are sent once in a couple of years. The worst credible consequence could be having the high value goods in mind, that are sent with the ship on a regular basis.

The result of this process element of identification of operator specific economic consequence data is a list with the relevant hazards in their specific formulation, associated with the respective costs:

It has to be emphasized that generic hazards and/or generic consequence data might lead to wrong decision support.

Identification of operator specific economic risk aversion

Risk aversion is expressed using measures for consequences drawn versus measures for likelihoods. Both the quality and the quantity should be in a format that reflects the operators way of thinking. The scale both of frequency and consequences depends on the specific business. For example, an operator might think in terms of the duration of a roundtrip, the time period for internal accounting, up to the envisaged time horizon of the operation.

For consequences, a similar approach should be chosen. Of most importance is, that monetary consequences are relevant and understandable to the operator.

Having the relevant scales for likelihoods and consequences, and their respective subdivision into bands, the next step is to identify those areas in the frequencies–consequences risk matrix, that are acceptable or intolerable for the operator. Acceptable is any combination of likelihood and consequences, that does not matter to the operator. Intolerable is any combination, that the operator cannot live with. The remaining part in between is the ALARP (As Low As Reasonable Practicable) area, where hazards lying in that area will be subject to a cost–benefit analysis (CBA). Only if the benefit exceeds the costs, hazard allocated in that area will be subject to risk reduction.

Identification of ship specific risk control options

Risk Control Options that are generally available to a sailing vessel are
- change of course,
- change of speed,
- change of status of motion stabilizing devices, and
- change of ballast,

or combinations thereof. During design, further RCO are available, like hull form design, specific layout of motion stabilizing devices, selection and layout of equipment, etc.

Besides the selection and application of RCO that are pertinent to design, a particular task within mode 3 is the analysis of the applicability and efficiency of the RCO available in mode 1. This task is closely linked to what is described in the following section, Preparation and calibration of ship data database for mode 1 and mode 2.

Preparation and calibration of ship data database for mode 1 and mode 2

Typical design work is the preparation of the stability documents for intact stability, the stability booklet. This document is based on contracted loading conditions. Additional loading conditions that cover the operation are carefully prepared and used in the subsequent process elements.

The process element of preparing representative operational loading conditions covers in first place the definition of ship varying data, in particular masses of payload, that is characterizing a particular loading condition. This step includes correct modelling of masses, including their extension in longitudinal, lateral and vertical dimension, as well as correct modelling of free surfaces.

When the loading conditions are defined, the sea keeping model i. e. the mass model with mathematical representation of the corresponding wetted hull surface is set up. As these models will be used by non-experts in an automated mode, this process element is critical.

In this part of the process, all three data groups ship operational data, ship varying data, and ship fixed data are first generated for those conditions that are relevant for mode 1. This creates three dataset with known uncertainties. These data sets are then compiled into one database, that is accessible in mode 1.

By this method the unknown uncertainties in the loading data from the loading computer in operation are overcome and replaced by quantifiable uncertainties.

2.3.2. Mode 2 - Training

The general approach in the training mode of ADOPT is not only the familiarisation with the system itself but also to give advise on the background of phenomena like parametric rolling and alike, as the purpose of the DSS only can be captured when the theoretical foundation is available. By this approach the training does not only customise the user on the system but also contributes to an improved situational awareness of the risks in specific sea states.

The Training concept consists of two modules with two sessions each, starting with general ship theory. Since the ADOPT-DSS is ship specific, the theory will afterwards be consolidated by exercises in the simulator demonstrating the vulnerability of the specific ship in particular seas. In the next session, the crew will be familiarized with using the DSS. This again starts with the theoretical description how the DSS works, which are its limitations, which are its modules and in which situations it can help. Afterwards, in the final module, the user will be customised in a simulator environment to get experience in using the system and improve his behaviour in critical situations.

Familiarization with the ship, theory

This module will start with the provision of the theoretical background on ships behaviours in general. It will explain what determines the movements of ships and how ships will move under specific conditions. It will give an introduction into rather new phenomena like e.g. parametric roll and how these phenomena are determined. It will make proposals how, without any technological help, the master can identify the risk of his current situations and how he generally could avoid too high risks. As the DSS is ship-specific, this module will consist of a 2nd part in which the theoretical background is applied to the specific ship. This part will make use of the experience gained during the design of the ship and present critical conditions for that specific ship in aspects of loading, sea state, etc. and how they could be avoided. It will give a detailed insight into that ship and present recommendations how this ship should be operated in different situations.

Familiarization with the ship, praxis

In this module the experience gained in the first module will be illustrated in practical exercises in a simulator environment. The main learning objective is the consolidation of the theoretical knowledge. To this purpose particular selected dangerous situations will be demonstrated to practically show how the specific ship will behave under those conditions. Afterwards strategies will be trained how to avoid these situations and how to operate the ship in them.

Familiarization with a mode 1 DSS, theory

After having laid the fundamentals in the previous modules, the student will need to be trained on the utilisation of the DSS. The DSS covers only some risks and has a specific approach. Thus the user will need to grasp the philosophy of the DSS in order to get an understanding when and how the DSS can help him. Therefore a clear introduction into the system has to be given, addressing its risk based approach, which hazards are covered and what limitations the system has. This will be complemented by an introduction into the application of the system and how the HMI will need to be used.

Familiarization with a mode 1 DSS, praxis

The final module will be again a practical exercise in a simulator environment, this time with the focus on training to sail the ship in difficult conditions with the assistance of a DSS. Several scenarios will be developed in which the student can prove that he knows how to deploy the DSS to achieve a status with lower risk. It will have to be tested if the user is able to assess situations right and derive the right conclusions. He will also have to prove that he knows the limitations of the DSS and is able to identify the situations in which the DSS can not assist him.

2.3.3. Mode 1 – Operation

The following requirements are of particular relevance for the operation mode:

- '1 – the dss shall be modular',
- '3 – the dss shall support real-time decision making',
- '4 – supported by a dss, the master shall improve his decision making under uncertainty',
- '7 – decision support shall have a time range of about one watch',
- '8 – The DSS shall operate on a ship while sailing',
- '9 – The DSS shall be operated and used by a ships crew',
- '19 – The DSS shall take into account extreme environmental conditions',
- '20 – The DSS shall take into account multiple wave systems',
- '24 – The DSS shall avoid misinterpretation of displayed information',
- '25 – The DSS shall avoid display of wrong information',
- '26 – The DSS shall be robust',
- '29 – The DSS shall display information of limitations in the displayed content',
- '32 – The DSS shall warn the user if risks arising from the identified hazards are beyond negligible',
- '34 – The DSS shall be able to perform a self-assessment',
- '37 – The DSS shall be ship-specific',
- '39 – The DSS shall resolve internal contradictions and provide consistent decisions support',

Mode 1 DSS without hard- and software support

Without support by a hard- and software implementation, mode 1 depends both on mode 2 – familiarization with the ship in theory and praxis – and the availability of guidance from mode 3 – operators guidance. The requirements No. 3, 4, and 24 are relevant only in that sense, that access to supporting information, e.g. an operators manual, must be prepared to allow easy access.

Requirement '4 – supported by a DSS, the master shall improve his decision making under uncertainty' is ensured by training in mode 2. This training provides the master with the expertise, that is necessary to improve his decision making. Relevant for operating a ship without a hard- and software implementation are still the requirements No. 9, 24, 25, and 37. These requirements have to be directly addressed in the preparation of a ship performance manual, and the set–up of training courses. Requirement No. 25 is subject to Quality Assurance in mode 3.

Mode 1 DSS with hard- and software support

Main components of the onboard installation are a wave sensor, a ship data database, fast and accurate motion prediction tools, and a Man Machine Interface. Within ADOPT, a wave radar is used for sensing the environment. The reason is, that only by using a radar it is possible to satisfy requirement No. 19. The numerical motion simulation tools are linear frequency domain ship responses for economic risks, and time domain ship responses with nonlinear roll motion for safety related risks. The MMI is embedded in the Conning Display.

To fulfil the requirement No. 3 and particularly 7 – decision support shall have a time range of about one watch all time consuming calculations are transferred to the mode 3 while all other calculations are performed during training or on board.

The inclusion of all uncertainties – uncertainties in the input data and numerical model etc. – require computational time in the range of months to a year with today's computer performance. Additionally many specifications of uncertainties are in itself highly uncertain. The probability of a hazard is calculated including only the variability of the seaway, neglecting uncertainties from wind, water depth, ship fixed data, ship varying data, ship operational data, the failure mode threshold and model uncertainties in the sea surface generator, numerical motion analyzor and sub mode load analyzor. The importance of the uncertainties is analyzed in mode 3. Time consuming are also the calculations to establish a correlation between ship motions and hazards. The calibration of the DSS for mode 1 by mode 3 consists partly in linking the considered hazards to ship motions.

Another part of the calibration of the DSS for mode 1 is due to the requirement 9 – The DSS shall be operated and used by a ships crew. Calculations that require personnel that is experienced/educated in ship theory are conveyed to mode 3 as well. This concerns the setup and input of the Numerical Sea Surface Generator and Numerical Motion Analyzor.

One step of the calibration of the mode 1 is the set up of the sea keeping model where for all relevant loading condition the mass model and a mathematical representation of the wetted hull surface is generated.

The ship varying data, loading condition and sea water density are combined into one set of ship data in the shipdata database characterized by measures such as KG, draught fore and aft and heeling angle, which are easily checked by the crew. According to these measures appropriate preassembled ship data are selected.

The preassembled ship data are only applicable in a narrow clearly defined range of the characterizing figures; KG, draught and heel. This approach presumes that the weight distribution does not vary significantly for a specific vessel with the same KG and floating condition and thereby neglecting these uncertainties related to loading conditions.

Preassembled ship data including the setup of the sea keeping model have the advantage that the hydrostatic and partly the hydrodynamic model are checked by an experienced person. Thereby eliminating the possibility of faults in the automatic or user defined generation of the sea keeping mode set-up in mode 1 – Operation. Further the frequently observed use of correction weights in the load master on board which introduces unacceptable faults in the mass model is avoided.

If no appropriate ship data are available the DSS does not proceed the calculations. If this occurs frequently, additional ship data must be generated onshore to cover the missing loading conditions.

The consequence of the combined requirements No. 34 and 25 – The DSS shall avoid display of wrong information, and 29 – The DSS shall display information of limitations in the displayed content, is that each module, data block, and interface shall have the possibility to stop the system or to inform the user. This makes the ADOPT–DSS an *Andon* system, as it was introduced in manufacturing processes by Toyota. The Toyota principle *Jidoka*, where Andon is a part of, aims at avoiding defects by immediately identifying potential defects and then solving them, in order to achieve improved quality.

Risk control options are:

- Heading,
- Speed,
- Status of active/passive motion damping devices, and
- Content of ballast tanks.

The hardware/software package of the ADOPT–DSS will compute speed and heading combinations around the present combination to deliver a more complete guidance to the master. The extend of this automatically calculated risk picture for the heading/speed combinations depends on the concrete implementation.

The master has the choice to select sets of heading and speed as user input. Based on the displayed information and the knowledge gained during "Mode 2 – Training" the master decides his actions.

2.4. Implementation concept

Figure 2-5 identifies all active modules (rectangular boxes) and data sets (trapezoidal boxes) that are relevant for a risk based decision support system. System components pertinent to the environment are shown in dark blue, system components pertinent to numerical calculation are shown in orange, components that relate to ship data in magenta, risk–based decision making in light blue, the Man-Machine-Interface in black.

Figure 2-5 shows, how design and operation are linked towards each other. As well the main interfaces either to input data (block arrows) or internally (nodes in grey) are unambiguously identified.

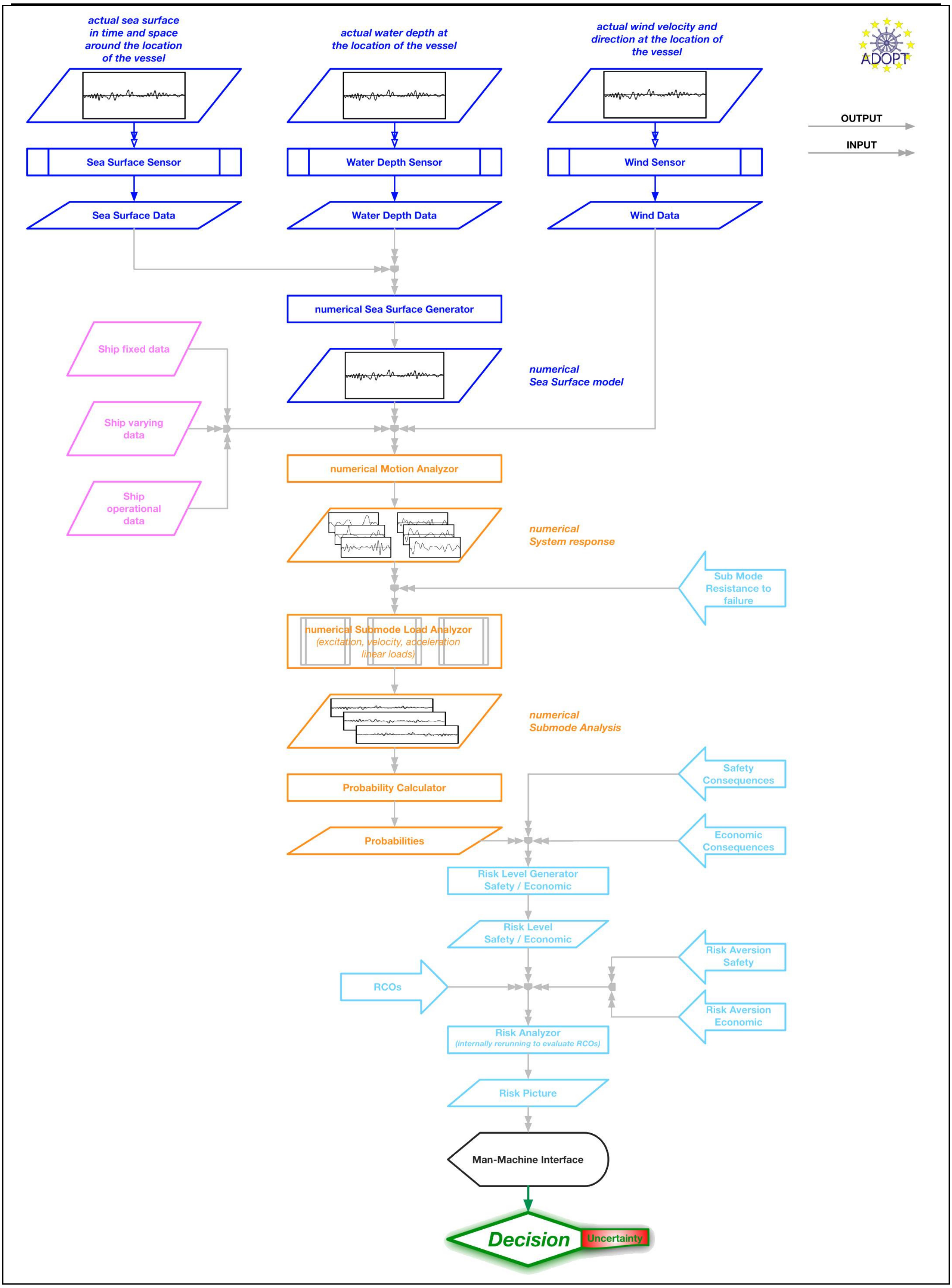


Figure 2-5: ADOPT Modules and data sets, for design and operation

Table 2-3 identifies, what hardware and software systems are selected and integrated in the respective modes.
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Module / Data Set	Mode 3	Mode 2	Mode 1
Sea Surface Sensor	Hindcast		Wave Radar
Water Depth Sensor	Hindcast / charts		NMEA bus
Wind Sensor	Hindcast / manual		Anemometer
Numerical Sea Surface Generator	Same implementation in all modes, NEWDRIFT and ROLLS		
Ship fixed data	Design database	Predefined ship data database	
Ship varying data	Design database	Predefined ship data database	
Ship operational data	Manual input		NMEA readings
Numerical motion analyzor	Same implemention in all modes, NEWDRIFT and ROLLS		
Numerical sub-mode load analyzor	CFD, FEM, ...	Calibrated data	
Probability calculator	Same implementation in all modes, PROBAN and ROLLS		
Submode failure mode threshold	Stress, strain, . . .	Relative excitations / velocities / accelerations between ship and water	
Safety consequence data	Frequency based, MSC/Circ.1023		
Economic consequence data	Operator specific		
Risk level generator	Same implementation in all modes, simple summation		
RCO's	Everything incl. hull form modification	Speed, heading, maybe roll dampers	
Risk aversion safety	Frequency based, MSC/Circ. 1023		
Risk aversion economic	Operator specific		
Risk analyzor	Same implementation all modes, simple comparison		
Man Machine interface	Design environment	Conning display	

Table 2-3: ADOPT components, implementation in the three modes

Details are given in EHRKE and others (2008), KRUGER and others (2008) and SPANOS and others (2008).

3. Ocean Environment Modelling for Use in ADOPT DSS

The numerical simulation of the ship response for the ADOPT DSS requires a reliable representation of the sea state, which has to be generated from different available environmental data sources including wind and wave information. Depending of the application mode of the ADOPT DSS data sources are: real time measurements onboard for ship operations or hindcast data for design and training. For the operational mode of the ADOPT DSS sea-state data will be measured by the Wave Monitoring System (WaMoS II) sensing system by using a X-band nautical radar that was developed for real-time monitoring of the surrounding ocean wave fields. The full two-dimensional frequency-direction wave spectrum and sea state parameters such as significant wave height, peak wave period and direction both for windsea and swell are derived. For the design and training mode long term hindcast data are used to cover a huge sample of sea states in a consistent way. Special emphasis is put on the two-dimensional frequency-direction wave spectrum as basic input to the ADOPT DSS to cover multimodal sea states. A methodology has been developed to calculate two-dimensional wave spectra according to the different kind of input data and a procedure to create irregular seaways out of those. The qualities of these data sets are examined and an attempt is made to quantify the related uncertainties. This Chapter will present the different data sources, the data flow and handling towards the ship response simulations module of the ADOPT DSS.

3.1. Introduction

Detailed knowledge about the environment is necessary to access the risk for a ship with respect to various hazards like large accelerations, large amplitude motions and related secondary effects. Besides water depth, winds, and currents the sea surface, represented by the sea state is the most important quantity to reflect the operational conditions of a vessel.

The research project ADOPT, *Tellkamp et al. (2008),* aims at developing a concept for a ship specific Decision Support System (DSS) covering three distinct modes of use (Design - mode 3; Training - mode 2; Operation - mode 1). For ADOPT, a module is developed, which provides the required environmental information for the different processing modules. This information includes:

- A representation of the sea surface for the ship motion analyzer and
- The associated uncertainties for the probability calculator

The three modes need different basic data sources. Whereas in operations (mode 3) real time measured data are necessary in training and design (mode 2 and 1) hindcast data are the appropriate choice. Therefore the aim is to development a methodology to generate representations of the sea surface for the ship motion calculations using different environmental input data sets including measured or modelled wind and wave information. Hence possible input data sets are examined, focussing on their quality as well as on their availability and are combined to make optimal use of those for the DSS. The accuracy of the appropriate wave components and wind forces that can be expected for the ship motion calculations are quantified for the uncertainty modelling in the limit state formulations.

These data sources are outlined in Section 3.2 and 3.3. Section 3.4 presents the concept of a module to combine the different data sources and the associated parameters, which describe the sea state, to a common product, which is passed to the motion analyzer.

3.2. Hindcast data for design and training mode

Ship design requires the use of realistic and reliable sea state and wind data. Therefore it is of great importance to have an unrestricted consistent long-term area-wide wave data set as a basic source for the ADOPT DSS. To achieve that objective a mathematical wave model has to be used. The approached described in the following is used in the ADOPT project for the North Sea and may serve as an example for other areas of interest.

3.2.1. The wave model

The appropriate tool for the computation of a ten years hindcast in the North Sea is the third generation wave model WAM Cycle 4.5, *Komen et al. (1994), Hasselmann et al. (1988)*. This state-of-the-art model runs describes the rate of change of the wave spectrum due to advection including shoaling and refraction, wind input, dissipation due to white capping, nonlinear wave-wave interaction and bottom friction. The model has been validated successfully in numerous applications and runs on a global or on regional scales at many institutions worldwide.

The sea state model is set-up for the North Sea between 51° N, 61° N, 3.5° W and 13.5° E. The spatial resolution of the wave model grid is $\Delta\prod$ * $\Delta\lambda$ = 0.05° * 0.1° (Δx corresponds to 5,38 km at 61° and 6,99 km at 51°, Δy = 5.5 km). Figure 3-1 shows the model domain, which includes 17592 sea points, and the used water depth distribution.

The driving wind fields have been computed at GKSS by the *RE*gional *MO*del REMO, *Jacob and Podzun (1997)* and are available in a one-hourly time step for the whole 10-years period. At the open boundaries of the REMO model grid the required information has been extracted from the re-analysis fields of the global atmosphere forecast system of the National Centres for Environmental Prediction.

At its open boundaries the ADOPT North Sea wave model uses the full two-dimensional spectral information provided by the SAFEDOR North Atlantic model.

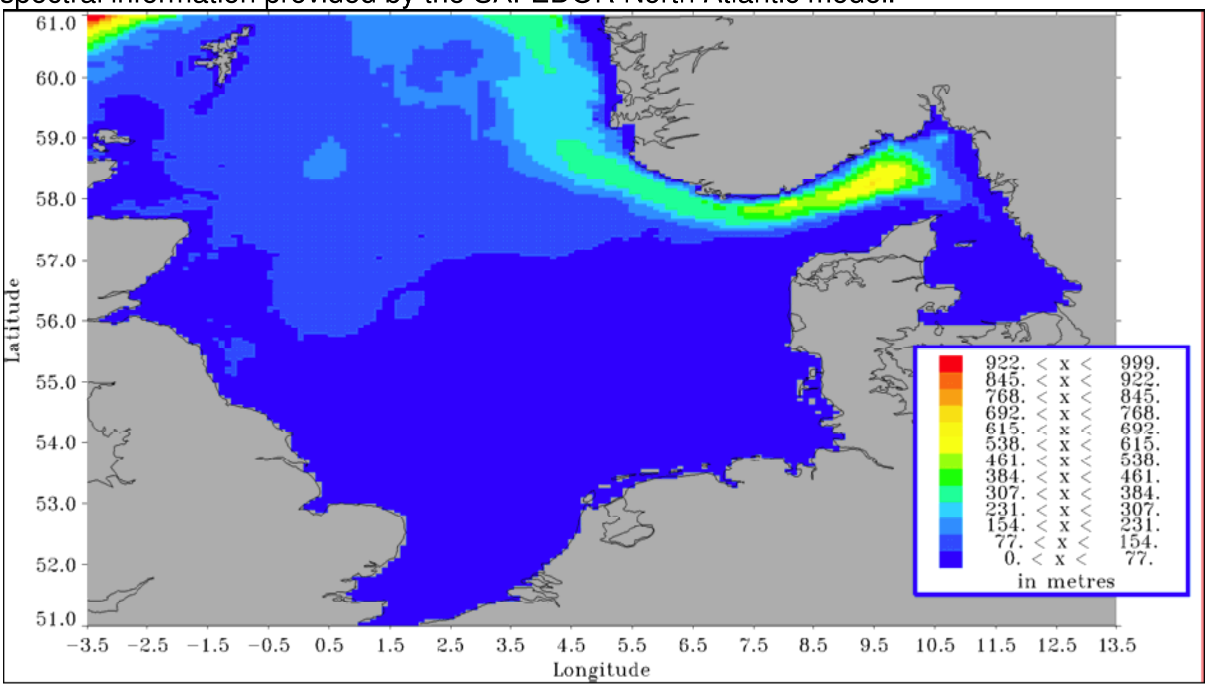


Figure 3-1 : Depth distribution for the ADOPT North Sea wave model grid in metres.

The wave hindcast system is implemented on the supercomputer of the German High Performance Computing Centre for Climate- and Earth System Research. The current configuration of that computer system includes 24 PVP (Parallel Vector Processing) -nodes (NEC *SX-6*) equipped with 8 CPUs each. To take advantage of this system a version of the wave model is used that uses the MPI (Message Passing Interface) software to run the program in parallel. The CPU-time consumption for the simulation of one year in nature is about 100 CPU-hours.

3.2.2. Wave model results

The results of the 10-years include 17 integrated wave parameters, which are listed in Table 3-1I, at every model sea point in one-hourly time steps in ASCII code for the time period 1990-01-01 (01 UTC) to 2000-01-01 (00 UTC). The full two-dimensional wave spectra for all active grid points are saved three-hourly in binary code.

Table 3-1: Integrated parameters included in the final wave data set

PARAMETER	UNIT
wind speed	metres/second
wind direction	degree
windsea mean direction	degree
windsea significant wave height	metres
windsea peak period	seconds
windsea period from 2nd moment	seconds
windsea directional spread	degree
swell mean direction	degree
swell significant wave height	metres
swell peak period	seconds
swell period from 2nd moment	seconds
swell directional spread	degree
mean direction	degree
significant wave height	metres
peak period	seconds
period from 2nd moment	seconds
directional spread	degree

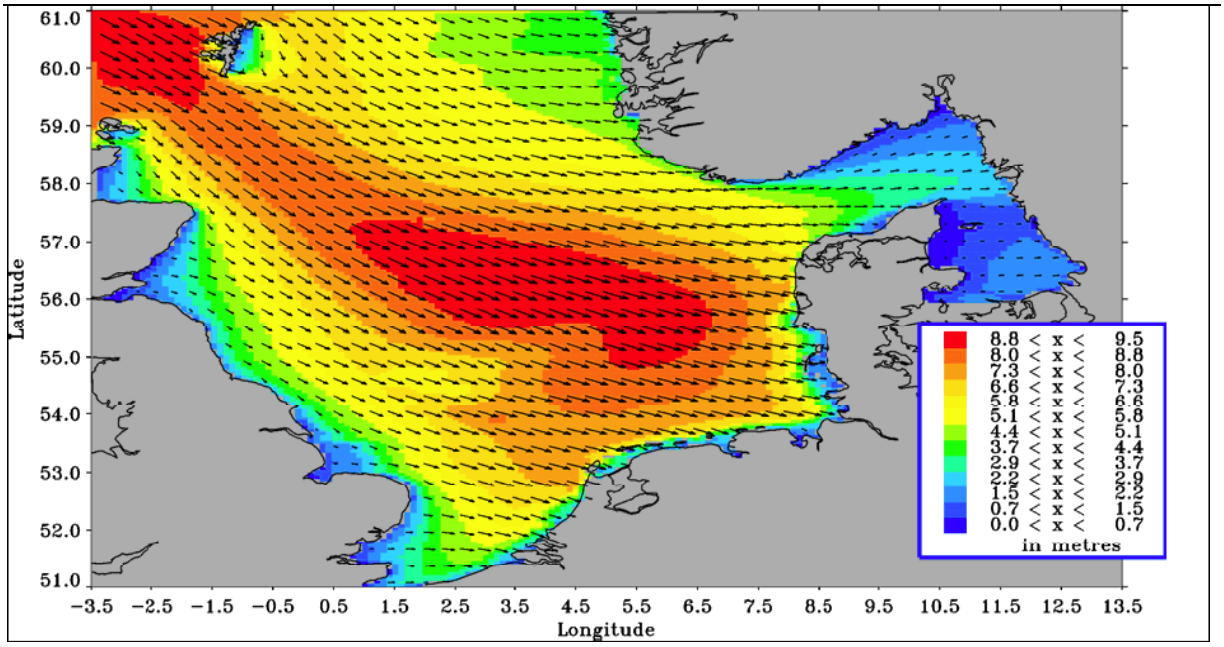


Figure 3-2 : Distribution of significant wave height in the North Sea on 1990-02-28, 00 UTC

Fig. 3-2 shows the computed significant wave heights and wave directions in the North Sea on February 2nd, 1990 at 00:00 UTC. At this time two storm areas are detected, one in the north-western corner of the model grid and another one in the central North Sea both with maximum significant wave heights around 9m. The waves at that time propagates from north-west to south-east, a scenario demonstrating the importance of the boundary information at the open boundaries of the model grid that have been extracted from the spectral information obtained by the SAFEDOR North Atlantic model.

For the verification of the wave model results and the quantification of the uncertainties of the computations appropriate quality procedures have been installed. Figure 3-3 shows as an example a time series plot of the computed and measured significant wave height, zero up-crossing wave period and mean wave direction at the platform K-13 located in the southern North Sea for the three-month period 1990-10-01 to 1991-01-01. These comparisons demonstrate that the wave model results agree fairly well with the measurements and prove that the model works accurate. The statistical analysis of the comparison of the computed and the measured significant wave heights at K-13 provides the statistical parameters given it Table 3-2.

Table 3-2 : Statistics for the time period 1990/10/01-1991/01/01, 00 UTC at K-13 (H_S)

significant wave height at K-13	value	unit
number of values	5575	
mean of measurements	1.59	m
bias	-0.06	m
root mean square	0.47	m
correlation coefficient	0.92	
slope of regression line	1,1	
reduction of variance	0.8	
scatter index	31	%

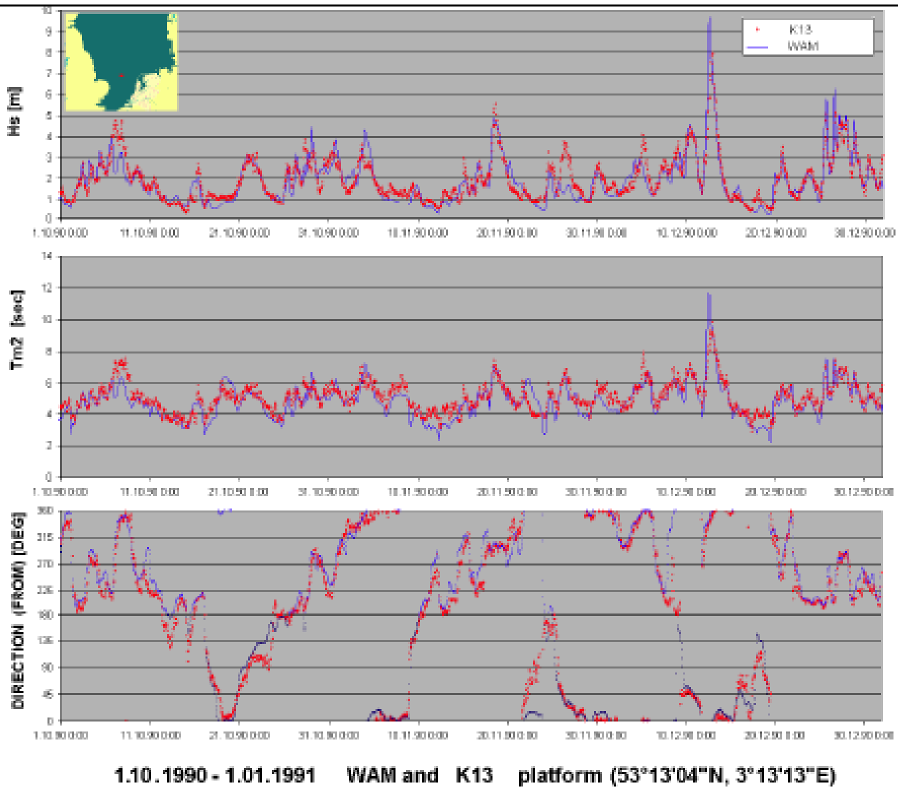


Figure 3-3 : Time series of measured and computed wave data at the location K-13

3.3. Real time measurements for operation mode

In the operational mode 1 safe and reliable estimates of environmental conditions are essential for the functionality of a DSS. Within the ADOPT project radar measurement are identified as the most advanced technique to collect as much information as possible about the wave systems and the winds. The WaMoS II wave radar was selected as a demonstrator and tested on board of the Tor Magnolia.

A WaMoS II raw data file consists of 32 subsequent radar images. The time interval between two measurements depends on the antenna repetition time, which was about 2.4s aboard Tor Magnolia. Each individual image in a sequence has a spatial resolution of 7.5 m, covering a circular area of approximately 4.2 km in diameter around the antenna position in the centre of the image. The backscattered radar intensity is digitised in relative units, linearly scaled to one byte. Figure 3-4 gives an impression of the appearance of a radar image (recorded on 2005-12-15 at 10:03 UTC). The colour coding in the figure corresponds to the radar backscatter strength in relative units. Black indicates no radar return and white maximum return. A circular area of 440 m in diameter in the image centre is blanked. Due to the measurement set-up, this area is not valuable for the purpose of wave measurements, as the radar signal will be disturbed by vessel constructions. In the remaining area, stripe-like wave patterns are clearly visible. These patterns are analysed to derive wave spectra and sea state parameters. For a standard measurement, this analysis is limited to so called analysis areas placed within the radar image. The three analysis areas chosen for the Tor Magnolia measurements are marked with red frames in Figure 3-4. For these areas, the directional wave spectra and all statistical sea state parameters are calculated. The spectra of all areas that passed the internal quality control are averaged, resulting into a mean spectrum representative for the entire area around the vessel.

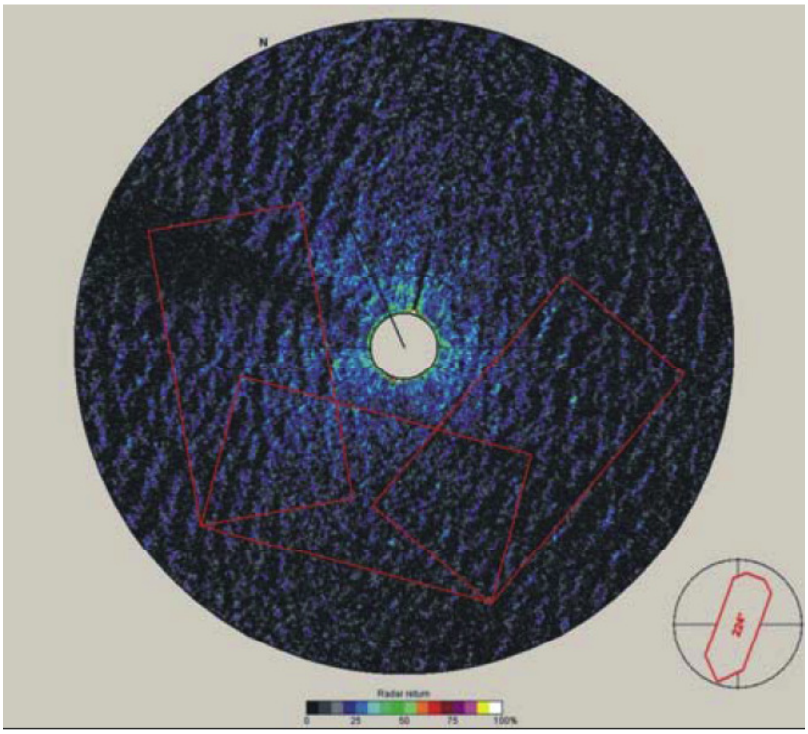


Figure 3-4 : Analysis areas of WaMoS II for Tor Magnolia (2005-12-15 at 10:03 UTC).

3.3.1. Quality control

An improved automatic quality control mechanism to exclude unsuitable or corrupted radar raw images from further analysis was developed to enhance the reliability of data acquisition and prevents system failures of the DSS. As technical background, each WaMoS II measurement is marked with a *quality control code* ('IQ') to distinguish between high and low radar raw data quality. A code number reflects both the nature of a disturbance as well as its impact on the results.

Especially for an on board installation of the system two main factors lead to wrong measurements:

1. Parts of the measurements are taken with the radar being operated in 'long pulse' mode. In this pulse setting, the radar images are blurred, making an accurate analysis of the images impossible [2].
2. In times when the 'Tor Magnolia' approaches or leaves a harbour, parts of the coastline or harbour constructions are visible in the radar images thus disturbing the wave analysis.

In addition, examples of less frequent sources of image disturbances are:

3. Signatures of passing ships within the analysis areas.
4. Heavy rainfall.

The new quality control is based on 14 quality parameters deduced from the grey levels of the radar images and the wave spectra computed from the images. The evaluations of these parameters are treated as a classification problem and image disturbances are sorted into 'classes' with defined properties. The quality control separates these classes by a cluster analysis algorithm. Figure 3-5 gives an impression on the overall performance of the algorithm. All measurements with unreliable high significant wave heights are detected and marked as belonging to one of the error classes. In particular, the extreme significant wave heights at the beginning and end of data gaps within the time series, resulting from harbour times of the vessel are indicated correctly. The red colour marks those data sets that belong to the 'harbour' error class. In addition, disturbances by small objects like ships are more frequent close to the harbour gaps in the time series, as can be expected. Another indicator for the good performance of the algorithm is the stability of the peak wave direction within the green areas.

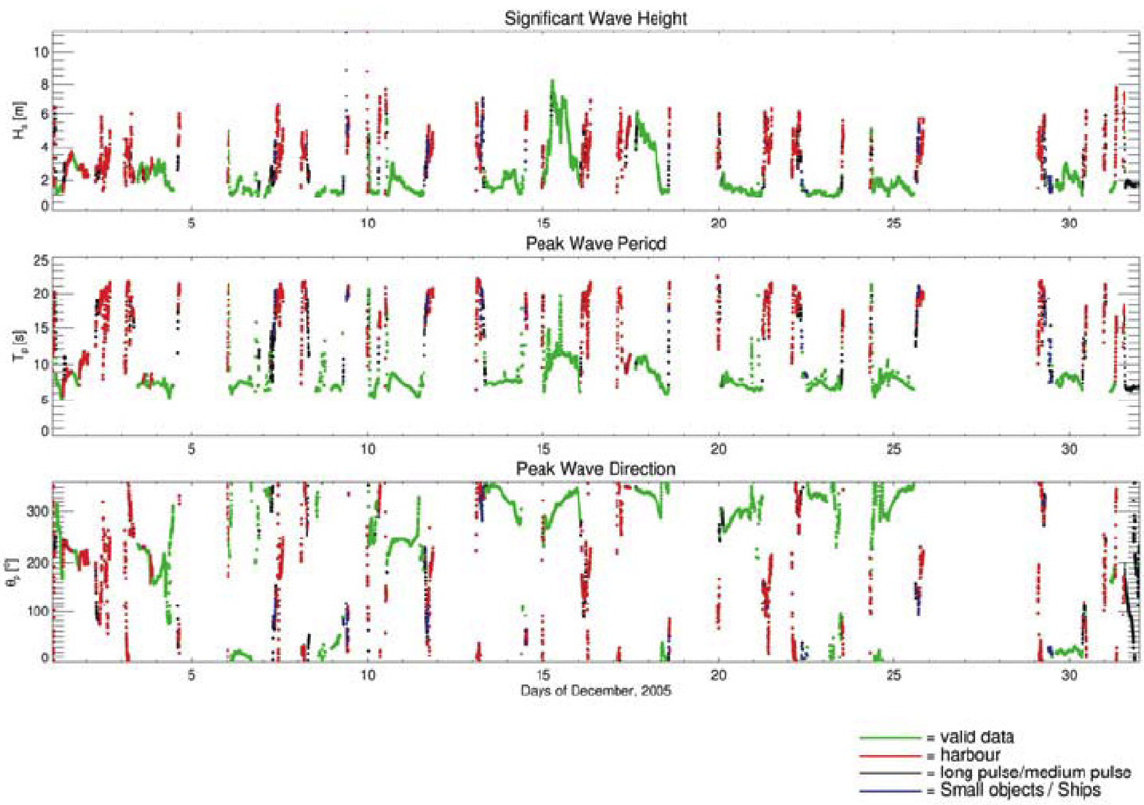


Figure 3-5 : Result of quality control marked in time series of sea state parameters.

3.3.2. Wind measurements

Usually, wind information is retrieved by sensors aboard a vessel. These measurements are often influenced by sensor position and the occurring error can be of the same magnitude as the measurement itself. A measurement technique that allows monitoring the wind on a larger area is a desirable complement to the standard data product. With such a method the wind measurements becomes more stable and in addition offers the opportunity to localise spatial variations in the area surrounding the vessel. Radar images are capable to provide this information, e.g. wind field measurements over open waters by radar are common practice in satellite remote sensing.

The imaging mechanism of wind signatures is based on the radar signatures of wind generated surface waves ('ripple waves') with wave lengths of a few centimetres. These waves develop instantaneously when wind blows over an open water surface. Their amplitude and shape is directly related to the surface wind speed. As radar sensors are sensitive to the roughness of a water surface, the ripple waves become visible in radar images. In satellite applications the backscatter is related to the local surface wind speed by semi-empirical models (e.g. CMOD-4). This measurement principle is transferred to nautical X-Band radar, because the imaging mechanism of wind is basically the same for all kinds of radar systems. Differences between satellite radar sensors and nautical X-Band radar in terms of spatial resolution, observed area, look angles and radar wave lengths prevent a direct application of the satellite algorithms to nautical radar images. In *Dankert and Horstmann (2005)* a neural network approach was used to relate the nautical radar signatures to wind speed and direction. For the ADOPT project a simplified method is developed.

The new method relates the mean grey levels directly to the wind speed. The mean grey level is the averaged grey level of 32 successive radar images. Figure 3-6 shows the correlation between the grey levels and the wind speeds measured by the standard wind sensor of the Tor Magnolia. The data are clustered into different wave height regimes. The data cover wind speed up to 30m/s and significant wave height up to 10m. A correlation of 0.89 reflects the very good agreement of mean image brightness and wind speed. In addition, the alignment of the data samples is independent on the significant wave height. In Figure 3-11, the wind speeds calculated from the radar images are compared to the wind measurements of the reference sensor. This time series shows only minor deviations and a standard deviation of 2.2m/s, demonstrating that radar images have the capability to serve as a wind sensor.

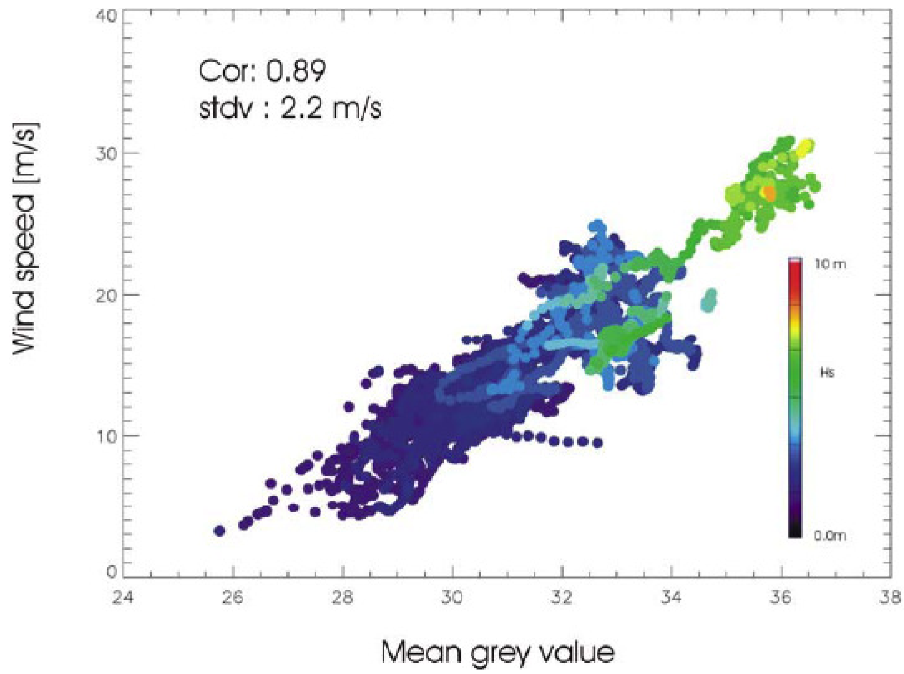


Figure 3-6 : Scatter diagram: Mean Grey value and wind speed.

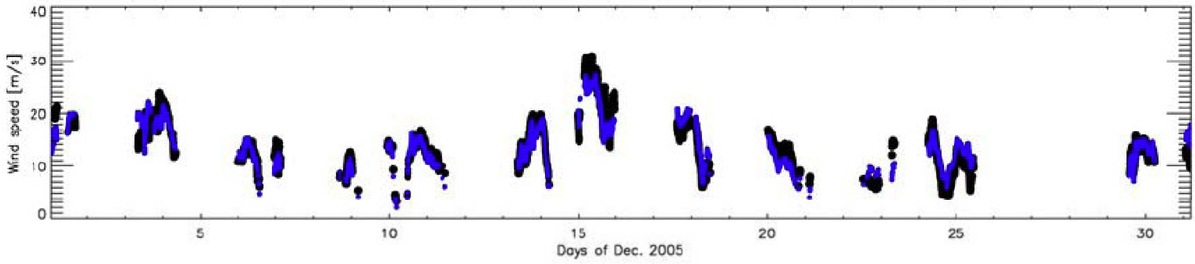


Figure 3-7 : Derived wind speed compared to reference

3.4. Combination of data for the numerical surface analyzer

The full information about the actual sea state at an arbitrary location at a certain time is given by the corresponding two-dimensional wave spectrum, but usually the description of sea state is reduced to a few numbers, e.g. significant wave height, peak period and peak direction. In state-of-the-art weather forecasting those are the typically distributed data so far. However, from mathematical wave model hindcasts and forecasts as well as from measurements, such as the wave radar data, a lot more information, e.g. the detailed energy distribution is available. Therefore the required environmental input for the DSS can be obtained from different data sets that may include integrated parameters only or two-dimensional spectra at the best.

One important basis for the DSS is the numerical simulation of the ship response to the actual sea state. To simulate the seaway required for the numerical motions simulation, the model needs directional sea state spectra as input data. A representation of the sea surface elevation η at each point $\mathbf{x}=(x,y)$ at a time t can be derived from the amplitudes of a directional spectrum by summing up the spectral components,

$$\eta(\mathbf{x},t)=\sum_{n=1}^{N} a_n \cos(\mathbf{k_n}\mathbf{x}-\omega_n t+\varphi_n) \qquad (3\text{-}1)$$

a_n denotes the spectral amplitude of a plane wave with angular frequency ω_n and wave number $\mathbf{k_n}=(k_x,k_y)$.

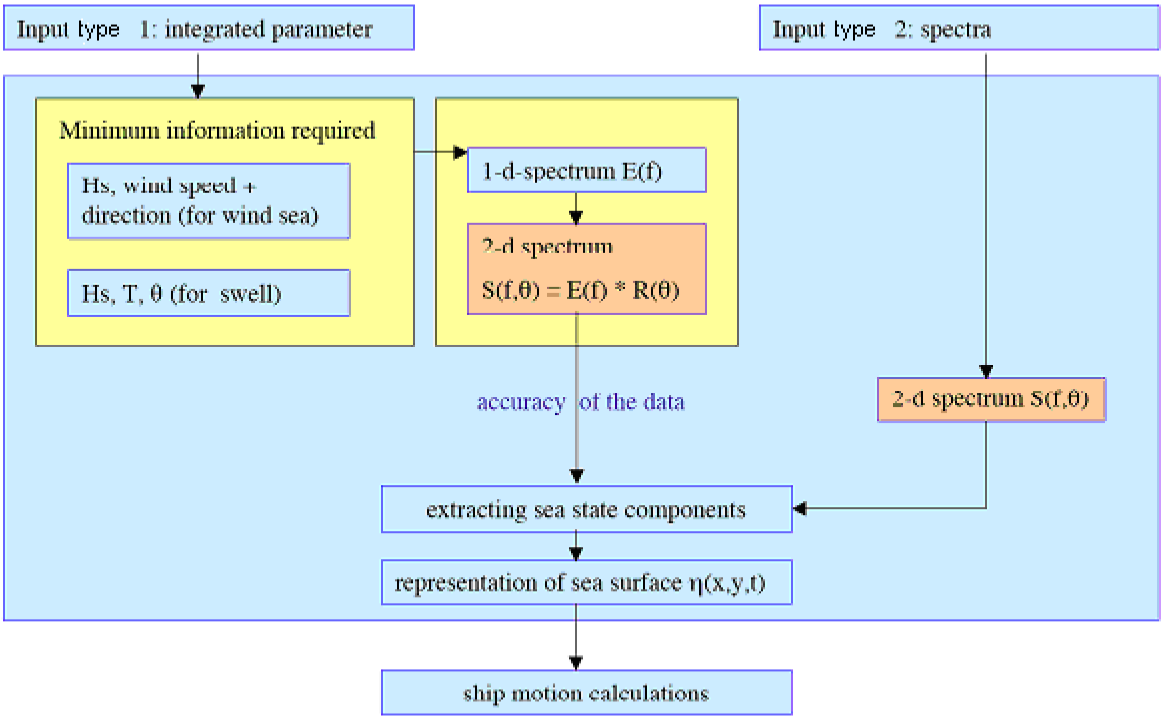


Figure 3-8 : Flowchart of the environmental data input into the DSS

The phases φ_n have to be generated randomly for each surface realisation. As $\boldsymbol{k}$ and ω are connected by the dispersion relation for ocean waves, the amplitudes can be expressed as a function of $\boldsymbol{k}$ or angular frequency ω and direction θ, respectively.

Thus, the directional sea state spectra contain all sea state information required for the simulation and it was decided to use it as the key data source. Therefore, the main task is to derive the directional spectra from the various available data sources for the generation of irregular seaways to provide the input for the ship motion calculations.

Figure 3-8 summarizes the dependencies between the different data inputs and gives a flowchart to combine the data. The proposed system is capable to be operated in two different modes:

- Input type 1: calculates directional spectra on a theoretical basis, derived from integrated sea state parameters.
- Input type 2: uses directly directional spectra from measurement or model computations.

Input data for both input modes can be wave model results or measurements.

3.4.1. Input Type 1

For the calculation of a theoretical two-dimensional wave spectrum from integrated sea state parameters the following quantities are the minimum requirement: Significant wave height (H_S), wind speed U and wind direction θ_U for wind sea and significant wave height, peak wave period (T_P), and the peak wave direction θ_P for a swell system. The sources for these parameters are wave model hindcast and forecast results or integrated parameters derived from WaMoS II measurements. The accuracy of the parameters is given in Table 3-3 for wave model data as well as for measured data. These parameters are used to calculate the JONSWAP spectrum. The directional spreading is estimated according to cosine-squared distribution. Those theoretical approaches were selected as they are widely used and well established. In a later stage of the project, additional theories can be included in the modular structure of the software to adjust the system to other wave climates.

Table 3-3: Accuracies for wave model and WaMoS II data

Parameter	**Range**	**accuracy**
For wave model results:		
Wind speed	0 – 35 m/s	± 20 %
Wind direction	0 - 360^0	± 10 %
Significant wave height	0 – 20 m	± 15% or ± 0.5m
Peak period	2.4 – 24 s	± 10%
Peak direction	0 - 360^0	± 15^0
For WaMoS II measurements:		
Wind speed		Approx.: ± 5 %
Wind direction		Approx.: ± 3^0
Significant wave height	0.5 – 20 m	± 10% or ± 0.5m
Peak period	3.5 – 20 s	± 0.5 s
Peak direction	0 - 360^0	± 2^0

3.4.2. Input Type 2

In Input Type 2 directional wave spectra are used as data input. For the DSS, the spectral components $a_n(\omega,\theta)$ are chosen as input data set and are directly taken without any further pre-processing from the wave spectra. The standard deviation for spectral components a_n is estimated to 32%, by adapting theoretical considerations for one-dimensional wave measurements to the WaMoS II temporal and spatial analysis.

3.5. Creating irregular seaways for numerical motion simulations from directional spectra

Given a directional spectrum the energy distribution of a certain seaway is dependent on two variables, namely the wave frequency and the encounter angle of the waves. Figure 3-9 shows a three dimensional plot of a directional spectrum. In this case the spectrum consists of two components: One wind sea component with the wave energy spread over a wide range of angles (here 180 degrees) and a swell component with a very narrow banded range of encounter angles.

The common and well-established way to generate irregular seaways for numerical motions simulations is to superpose a finite number n of regular wave components. The superposition principle is valid as long as linear wave theory is used. This seems to be sufficiently accurate for the prediction of ship motions, as the error in the surface elevation, which is most important parameter for such kind of problem, is moderate according to *Stempinski (2003).*

Equation [3-1] shows the position- and time dependent wave elevation following the superposition approach for long crested waves.

The individual amplitudes for each component are obtained by dividing the given spectrum is divided into n strips: either equidistant or in such way that all strips contain the same resulting wave energy (constant-amplitude approach). When using a relatively small amount of wave components, the latter approach still provides a good resolution of the peak region of the wave spectrum. In order to avoid a periodicity of the generated seaway, the frequencies ω_n of the wave components are randomly chosen within the component individual frequency band, assuming a uniform distribution. Besides the encounter angle and the frequency, the phasing of the wave components is important for the generation of a natural seaway. The phase shift φ_n is also randomly chosen for each component due to the reasons mentioned above.

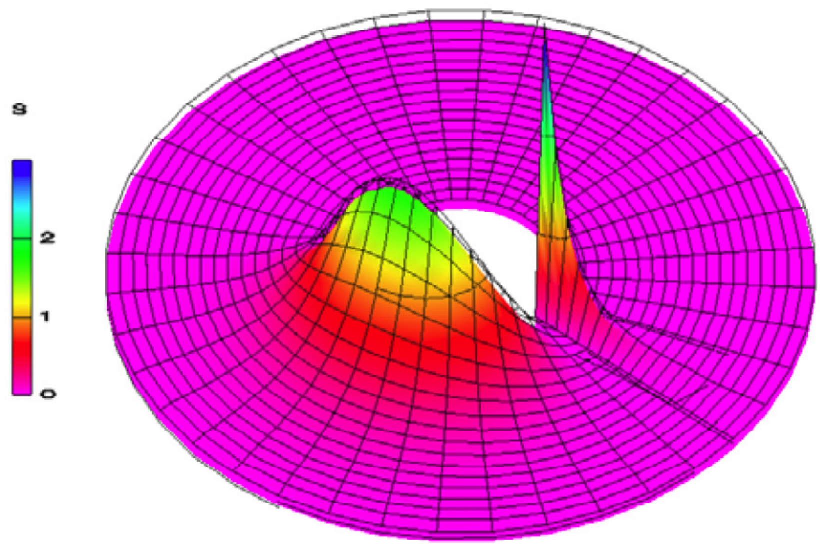


Figure 3-9: Bi-modal directional wave spectrum

Figure 3-10 shows a time series recorded amidships in a ship-fixed coordinate frame for a time interval of 1000 seconds, which is obtained from the wave spectrum shown in Figure 3-9. The ship speed is equal to zero in the given example, thus the encounter frequency equals the wave frequency in this case.

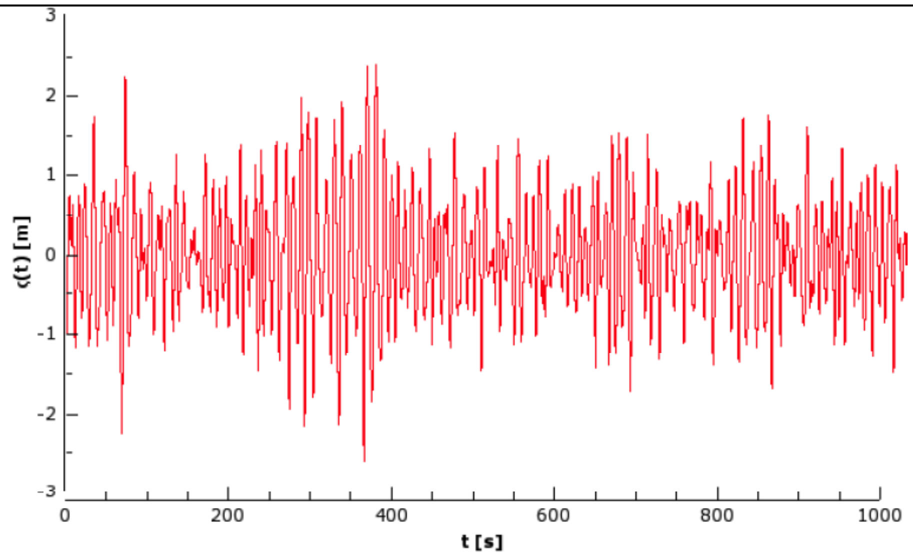


Figure 3-10: Time series of wave elevation amidships

3.6. Conclusions and needs for further development

Different environmental data sets including wind and wave measurements or wave model results are identified as possible input for the DSS and an attempt is made to quantify the accuracy of those. Since the two-dimensional wave spectra is the key source for the generation of sea surface representations, all available spectral data can be used directly whereas the integrated wave data must be processed to obtain the required spectra. The corresponding algorithms are outlined. The two-dimensional wave spectra will always be the base for the creation of irregular seaways for the numerical motion simulations and the method to generate those sea state representations are presented. Finally, the treatment of the different environmental input data is evident, the chain of all required steps of the methodology from input via two-dimensional wave spectra to the creation of irregular seaways is clearly resolved and the related uncertainties are discussed. The methodology developed and described will be realised and implemented into the ADOPT DSS.

As part of the ADOPT project algorithms in WaMoS II were improved and detailed spectral information about the wave field can now be offered realtime by the WaMoS II system for realtime ADOPT like Decision Support Systems

4. The probabilistic Method within a risk Assessment Framework

4.1.1. The Probabilistic Core of a Decision Support System

The herein probabilistic seakeeping method has been developed for application within a risk assessment environment where the probability of specific events is routinely evaluated. Moreover, the risk assessment could be an integral part of a decision support method. The domain of the seakeeping analysis, the nature of the possible events and the frequency of the evaluations as imposed by the assumed decision process specify the set of requirements for a suitable probabilistic method.

The ADOPT-DSS has been considered as the framework for the development of the risk assessment method. Within this framework a generic risk aversion approach of the DSS is assumed along with the more specific one recently introduced by *Spanos et al.* (2008) and which is also applicable to the ADOPT-DSS. The generic approach attempts the evaluation of the risk related to the current sailing conditions and on the basis of some existing risk requirements set by the ship operator and the society. In the latter the risk mitigation is rigorously based on the relative risk between alternative sailing conditions, searching for all feasible risk mitigation options, and as a consequence results to a more demanding performance for the probabilistic method.

In the assumed onboard risk analysis the hazardous events related to seakeeping behavior of the intact ship are identified and appropriately formulated. Then the probability of those events can be numerically estimated exploiting specific information available onboard. Given these probabilities and assuming corresponding consequences (which may be economic or safety related) the risk evaluation follows. Alternative sailing conditions of lower risk can be explored by the DSS and any identified Risk Control Options (RCOs), the final outcome of the DSS process, can be disposed to the ship master in support of his navigational function.

In the next Figure 4-1 the probability evaluation is defined as a nested module (dashed line) within the risk assessment of the DSS. The module is assumed appropriately interfaced to the data modules, which refer to the prevailing wave environment condition for which the risk is assessed, the specific ship loading and operational conditions, the necessary information for the definition of the hazards and the related limit states. Furthermore, risk controls are those parameters that could practically affect the probabilities hence the related risk, while the outcome of this process is the probabilities of any events in question. The computational core of the probabilistic module comprises of two sub-modules the seakeeping and the probabilistic analysis, each implemented with appropriate computer program. Generally, this basic computational structure is rather heavy and up to impractical for onboard applications where the time available for computations is quite limited. Thus, an efficient probabilistic approach for this purpose has been developed as detailed in the followings.

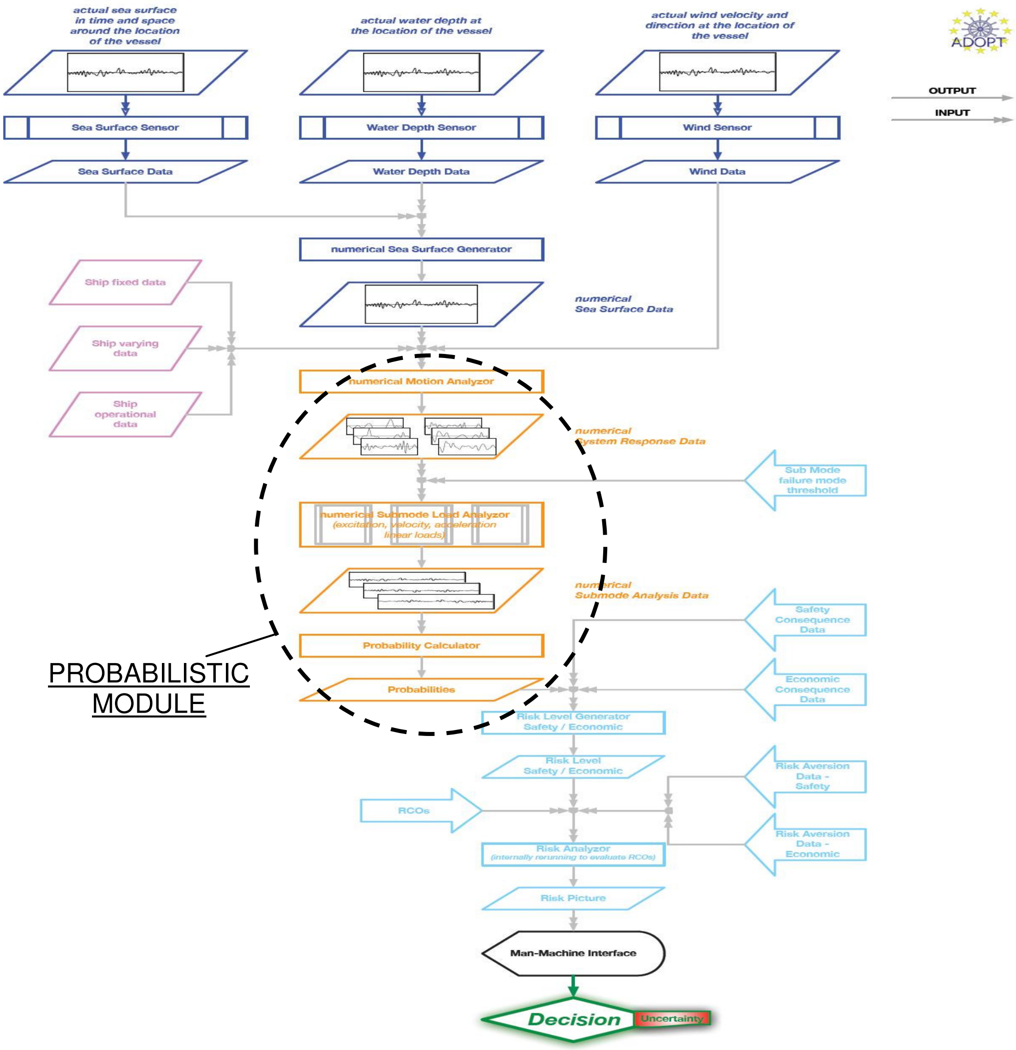


Figure 4-1 The probabilistic module within the risk assessment framework

4.1.2. Low Probability Events

Most of her life time a modern ship will operate within safe operational boundaries that should have been explored during her design stage, while occasionally, she will encounter hazardous situations when she operates close to or even beyond the safety boundaries. These undesired and dangerous situations might have been considered in the ship design stage and could be addressed in certain way by proper master's training or qualitative guidance to the master (IMO, 1995, 2007); although they are limited and correlated with some low probability of occurrence, the key point here is that they may result to considerable or very serious and even up to catastrophic consequences. In other words, during the ship operation some risk is always assumed by the ship operator that is related to situations of low probability with non-zero consequences.

Since the hazards concerned are related to the seakeeping performance of the ship they would occur with the characteristic frequency of the sea wave effects. Considering the level of analysis and accuracy achieved by the probabilistic approach (sec. 4.2.1), very low probability events of less than 1.0E-03 are *not* herein addressed. Hence low probability events are assumed those events that could occur once in hour and up to once in three hours.

4.1.3. Hazards Identification

In the context of the risk assessment as hazard is assumed any specific undesired event that depends on the seakeeping of the intact ship. To characterize an event as undesired it should be related to some quantifiable consequences. These hazards should be identified and defined in advance and they are considered as a valuable input to the evaluation procedure. The herein identified hazards have been based on the hazard identification procedure conducted by *Skjong et al.* (2005), where experts from different fields and various backgrounds contribute with their experience to identify and sort hazardous events for intact ships in waves in view of severity and frequency.

Such hazards encompass a wide range from structural failures, stability problems, shift, damage or loss of cargo, and efficiency/economical aspects like delays and passenger seasickness that directly affect the economy and reputation of the provided maritime services. Having identified such a long list of possible seaway related hazards for a specific ship it follows the formulation of the related limit states and the assessment of consequences. The formulation of a limit state (sec.4.1.6) is the expression of a hazard as function mainly of the ship responses and the definition of characteristic events by use of the threshold values (sec.4.1.4). Thus any hazard has eventually been translated into a mathematical expression, namely a single variable, that its probabilistic properties are quantified by application of the herein discussed probabilistic method.

4.1.4. Threshold Values

The hazards are defined through a set of characteristic threshold values for the involved variables. For example suppose the hazard of the frequent propeller racing that may occur during severe pitching and subsequent propeller emergences. Such an event is undesired to the propulsion system. So, analyzing the capacity of the propulsion system and its tolerance to the racing, independently of the ship motions, then the threshold value for the racing rate can be determined as the maximum number of racings that consequences can be assumed to be negligible. If the racing frequency is higher than the determined threshold value then the related consequences will be encountered. Apparently for a hazard on a top level description several threshold values may be derived each one correlated to a different level of consequences.

4.1.5. Environmental conditions

A powerful onboard guidance to the master is determined by its ability to assess the performance of the ship in response to the actual prevailing wave conditions. In case of lack of sufficient wave information then the embedded seakeeping assessment has to be based on assumptions, which inevitably lead to a broader assessment of possible events and their consequences that gradually may lead to failure to address the current situation. The presently assumed DSS and subsequently the probabilistic analysis incorporates provisions of measuring and reliably estimating the prevailing wave conditions and include anyway information about forecasted wave parameters (see section 3. The final outcome of processing of this wave information is a two dimensional (encounter frequency and heading) wave spectrum and its integrated parameters like the significant wave height and peak period. Currently the assumed most advanced approach to this purpose are radar based measurements, which exploit installed nautical X-band radars on the ship to generate maps of the sea elevation around the sailing ship and then calculate the wave properties and related sea spectra, Dannenberg, (2007). The variable sea state during a trip, as measured onboard comprises the basic source of randomness of the probabilistic problem.

4.1.6. Hazards formulation

Following a formulation likewise that used in structural reliability analysis any hazard of interest is formulated with a Limit State Function, which is a function of the basic variables and which is positively valued when the ship remains safe and negatively when unsafe, namely when the hazard occurs. The basic problem is reduced to the problem of calculating the small probability that

$$g(X_1, X_2, ..., X_N) < 0 \qquad (4\text{-}1)$$

where $\mathbf{X}=(X_1,X_2,\ldots,X_N)$ is a vector of basic random variables and g is referred to as the limit state function. Failure is defined by an event that $g(\mathbf{X})<0$, which is trivially the convention for the definition of failure.

The value of g-function is a random variable. Its distribution function is determined by the g-function itself and the probabilistic distribution of the basic random variables X. The variables describe functional relationships in the physical model as well as the randomness in the modeling. In simple cases the g-function can be reduced to some explicit mathematical/analytical formula. However in practical cases and especially herein when seakeeping is addressed this is a complicated function resulting from discrete calculations of numerical solvers, thus its evaluation results only numerically possible.

4.1.7. Ship Motion Model

The formulation and the evaluation of the g-function are determined by the nature of the hazards. The present g-functions are mainly functions of ship responses in waves. As denoted by the next two equations (4-2) and (4-3), g is function of the wave and loading parameters X and the ship responses Y, for some given response control parameters C, while the S function is the employed ship motion model.

$$g = g(X, Y \mid C) \qquad (4\text{-}2)$$

$$Y = S(X \mid C) \qquad (4\text{-}3)$$

For hazards for which a linear seakeeping analysis with respect to the incident seaway is satisfactory, a linear seakeeping code in frequency domain can be employed for the implementation of the S-function. In such cases the basic properties of linear systems are utilized to derive closed form expressions for the probability of the involved random variables. Independently of the possible linearity of the seakeeping analysis, it should be noted that both functions g and S are generally non-linear functions with respect to some X parameters and C response controls. On the other side, hazards related generally to non-linear ship responses in waves require suitable non-linear motion codes for their reliable assessment, which are implemented in the time domain.

For instance the severe accelerations at bow of a ship in heavy seas may be treated within the frequency domain as they are dominated by the vertical plane ship motions (heave and pitch), which can be satisfactorily approached by linear ship motion theory and related numerical codes. For this case a Frequency Domain Implementation – FDI of a DSS would be adequate. Whereas, for the non-linear stability problem of the parametric rolling in waves the solution can be approached only by a code where appropriate non-linear equations of motion are solved in the time domain. In this case a Time Domain Implementation – TDI of a DSS is required. In the following sections, the probabilistic evaluation of the g-function with an FDI of the S-function is discussed.

4.1.8. Uncertainties

In the ship motion problem there are input variables that are random like the incident seaway exciting forces, and dependent variables like the heave motion and responses in general, which are eventually random due to their dependence (S-function of sec. 4.1.7) on the random input variables. The ship motion problem is complemented by the parameters of the set problem, like the loading condition the ship forward speed and the heading to waves. In the herein formulation the set of parameters are assumed to be correlated to some degree of uncertainty, namely they are assumed to follow a probability model instead of having fixed values.

Suppose the loading condition of a ship which is specified through the ship displacement her center of gravity and the mass moments of inertia. In the practice of ship operation these values can not be determined in absolute accuracy (in some cases, they not even known at all). Hence, each parameter is assumed following a probability model e.g. a normal distribution around the best estimated value and some empirical deviation. Other probability models for the uncertainties may be also employed in a straight forward way. Therefore all the parameters can be formulated as random variables, which extend the initial set of random variables.

A parameter is considered for randomization (uncertainty) according to the impact of the uncertainty on the hazard probabilities. While if hazards probabilities are tolerable to such variations then parameter is still considered as deterministic. So far, it has been verified that the uncertainty of parameters affecting to the frequency dependence of ship's seakeeping, cause a stronger variation of the ship responses. A typical example of this is the effect of the uncertainty on the GM and the roll radius of gyration on ship's roll natural period (*Papanikolaou et al.* (1997)). Two other examples are commented in the following: When a two parameters JONSWAP spectrum for the sea waves is employed, the uncertainty of the peak period T_p of the spectrum considerably affects the ship responses, for the frequencies of main interest. Figure 4-2 shows a characteristic case, where the mean out-crossing rate of level 0.981 m/s^2 (=0.1g) for the vertical acceleration at the bow of a RoRo ship advancing with 15 kn in head waves of H_s = 4.0 m and T_p = 10.0 sec is scattered when assuming a small uncertainty of just σ_{Tp}=0.2 sec on T_p (where σ is the standard deviation), while all the other parameters are fixed. The scatter may be modeled by an asymmetrical distribution having a peak value around 600 out-crossings per hour.

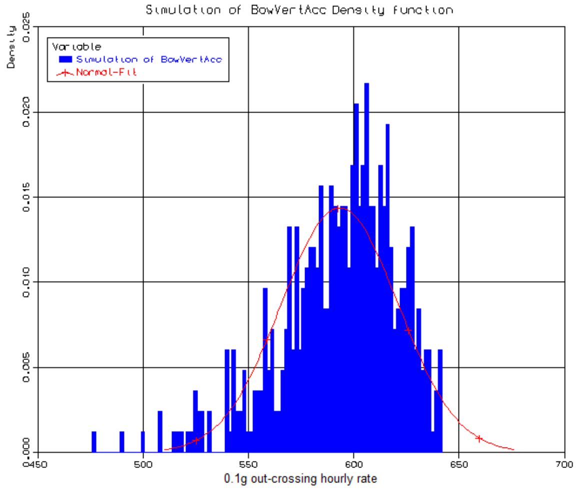


Figure 4-2 Distribution of the out-crossing rate of the vow vertical acceleration due to uncertainty on T_p

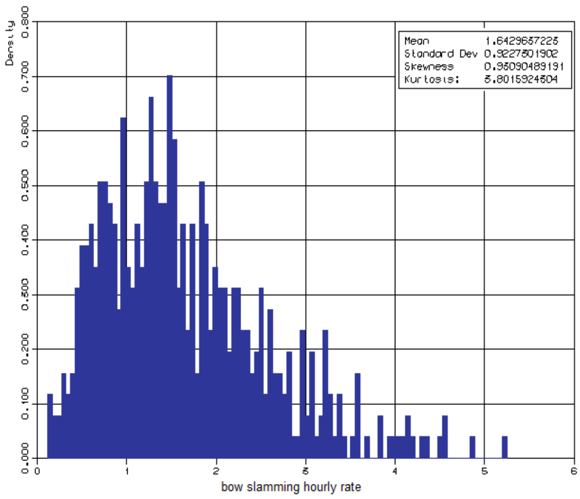


Figure 4-3 Distribution of bow slamming rate, due to uncertainty on H_s and T_p

A second example for the calculated responses of the ship with uncertainty is the bow slamming, shown in Figure 4-3, for the same RoRo vessel as it advances in waves with 15 kn and 160 deg wave heading (H_s = 5.0 m, σ_{Hs}=0.2 m and T_p = 10.0 sec, σ_{Tp}=0.2 sec). If for this case the wave information were perfect, namely without any uncertainty on H_s and T_p, then an average value of 1.5 slamming events per hour would be expected. Here under that imperfect information regarding the parameters of the wave spectrum, the slamming rate might be up to 5 events per hour. The introduction of uncertainty into calculations consistently broadens the range of the probable events as a consequence of the less available information.

4.1.9. Seakeeping events

Five limit states (hazards) have been elaborated, related to the bow vertical acceleration, the total acceleration at the bridge, the bow slamming, the propeller racing and the deck immersion (green water). Hazards are defined either as excessive acceleration (exceeding threshold values) or high number of occurrences of events. The hazards considered mainly depend on the vertical plane ship motions and they are consistent with the basic assumption of linear ship responses, underlying the FDI implementation of DSS. They are defined for several locations along the ship, which may be readily modified. Other hazards (e.g. bending moments etc.) may be included similarly. Considering that the efficiency of the probabilistic method greatly depends on the hazard's nature (section 4.2), any new hazard introduced should be investigated beforehand for appropriateness with respect to the employed FDI.

The related limit states results to the evaluation of the mean up-crossing (or out-crossing) rates of the involved variables. For Gaussian, zero-mean, narrow-band processes, the mean up-crossing rate v^+ of a level α can be approached by

$$v^+ = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}\exp\left(-\frac{\alpha^2}{2m_0}\right) \qquad (4\text{-}4)$$

where m_0, m_2 are the zero and second order moment of the variable's spectrum S_R in consideration. For linear ship responses S_R can be calculated from the transformation of the wave spectrums according to the response operator H, both functions of frequency ω.

$$S_R(\omega) = \left|H(\omega)\right|^2 S(\omega) \qquad (4\text{-}5)$$

4.2. The probabilistic Assessment

4.2.1. Monte Carlo Simulations

To deal with events of low probability the employed probabilistic method should be capable and efficient enough for the asymptotic behavior of the involved probability distributions at tails. Then the employed probability simulation methods that are based on a sampling of the evaluated function will suffer by the huge number of simulations as necessary to achieve a certain level of accuracy. In the Figure 4-4, the attained accuracy as a function of the number of Monte Carlo simulations for the limit state of excessive acceleration at the bow is shown.

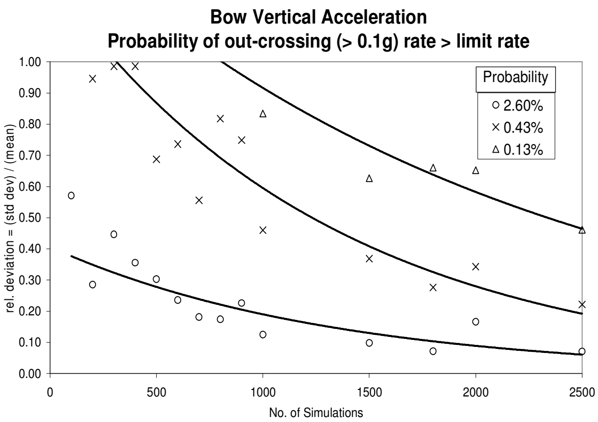


Figure 4-4 Monte Carlo simulations for low probability events of bow vertical acceleration

When the hazard is characterized by a low, but still considerable probability (2.60%) then an accuracy of 10% could be attained after 2000 simulations. For even lower probability event (0.13%) the relative deviation remain high 50% even after 2500 simulations. The Monte Carlo method has been used as a basis for comparison of alternative probabilistic methods, although the method itself proves efficient for the calculation of the central part of the distribution.

The deviation of 50% for the low probability becomes significant in view of the related consequences and particularly when they were high enough. In such cases a large deviation would have a significant impact on the total risk.

For the practical application of the risk evaluation method onboard and taking into account current PC hardware computational capabilities, the number of simulations should be of the order of 100. Hence 2000 simulations have been proved quite excessive for application of DSS. Thus, alternative probability evaluation methods are discussed in the next.

4.2.2. Reliability Methods

The applicability and efficiency of the First Order Reliability Method (FORM) for the evaluation of the probabilities of the set hazards has been investigated. The basic concept of the reliability method is briefly outlined below, for more details refer to *Hansen et al.* (2007), *Ditlevsen and Madsen* (2005).

As the g-function is generally not explicitly known but it can be numerically evaluated and processed, an approximation of this function is attempted. The method initially transforms the basic X-variable space of a formulated limit state function g(X) into a u-space, where variables U_i are independent and standard normal variables. The mapping does not change the distribution of the g-variable and preserves all relevant probability information. In this way the transformed g-function divides the u-space in safe and failure domain, see Figure 4-5, where $g>0$ and $g<0$ respectively. Then, if the g-function is substituted by a linear function which is passing through a point u^*, the so called design point, which is the point of the g-function closest to the space origin, a first order approximation is defined, namely the FORM method. Thus, the failure probability is that corresponding to the sub-domain defined by the linear approximation instead of the actual g-function (the shaded set in figure 4-5). Applying the same concept, but implementing a second order approximation then the SORM (Second Order Reliability) method is defined.

Obviously if the limit surface g of a hazard is not strongly non-linear then the approximation defined by FORM and corresponding probabilities could be satisfactory in view of the accuracy for the set problem. Therefore the efficiency of the method for the DSS purpose can be judged only by domain analysis and thorough understanding of each hazard and its dependence on the related variables.

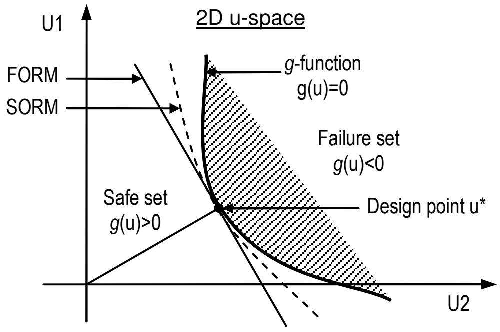


Figure 4-5 2D *g*-function approach with FORM

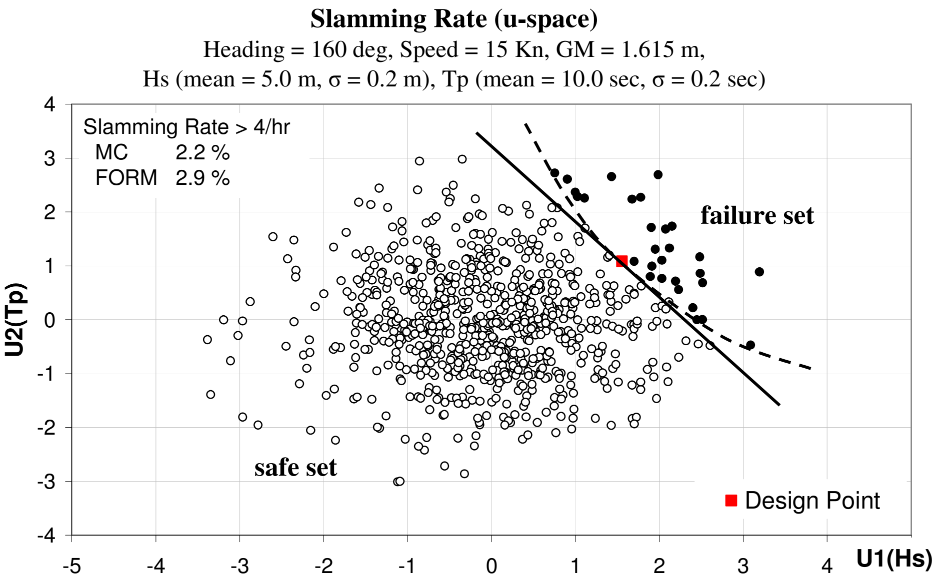


Figure 4-6 *U*-space for H_s and T_p in operational mode

Figure 4-6 presents the u-space mapping of a representative case, where the g-function (dashed line) divides the domain into failure (full symbols) and safe (open symbols) sub-domains. The straight line (full line) is the linear approximation of the g-function according to FORM. The shown samples (symbols) are the results of a corresponding Monte Carlo simulation.

The elaboration of the hazards, considered herein, has indicated that the g-function is not strongly non-linear, while it mostly defines convex failure sets; hence the probabilities obtained with FORM were systematically overestimated. This bias on the probability estimations is obviously a valuable property for the reliability of the DSS, particularly when employ the differential risk evaluation, *Spanos et al.* (2008).

With respect to accuracy and reliability of results, the method could be approved at least for the operational mode of DSS (section 5.2.5) where two dimensional limit states are addressed. When dealing with more complicated assessment problems, like with the design problem (design mode of DSS), where multiple variables need to be taken into consideration, relevant studies were not conclusive.

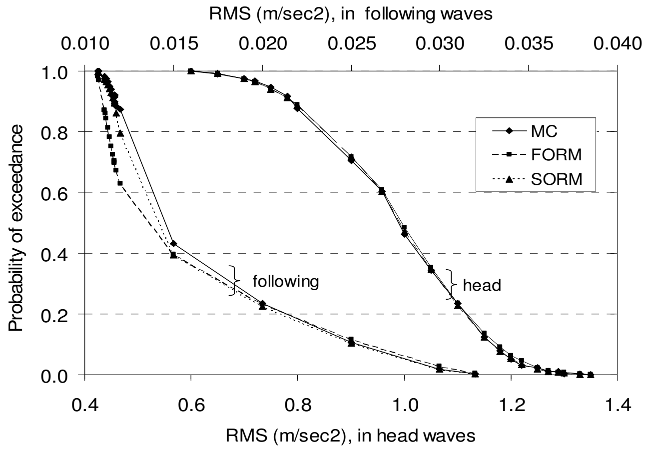


Figure 4-7 Probability of the vertical bow acceleration

Figure 4-7 presents the probability of exceedance of an acceleration level at ship's bow as determined with three different probability assessment methods, namely Monte Carlo, FORM and SORM. All the methods converge for the lower probability levels, whereas differences are notable in the left part of the diagram, namely for the higher probabilities, and the particular case of the following waves. However, in the range of lower probabilities, where the main interest for the DSS is defined, the FORM behavior has been found convergent. Based on such findings it could be concluded that when high probabilities were encountered then estimations by FORM should be verified by use of an additional Monte Carlo simulation, which is expected to converge with reasonable number of trials as the probability level is already considerable.

5. Numerical simulation – frequency domain implementation

5.1. Introduction

In realistic situations like those encountered by a ship in open seas during a voyage, each parameter of the seakeeping problem, even sensitive to seakeeping ship inherent data like GM and radius of gyration, is related to a degree of uncertainty, whereas other parameters, like environmental data, are inherently random. Above uncertain parameters and random variables define an intricate probabilistic short time assessment problem, the solution of which has beyond complexity increased time calculation/processing and reliability requirements for onboard applications.

With the current onboard seakeeping assessment it is attempted to exploit the practically possible determination of the sailing conditions, which are the basis for the probabilistic estimation of seakeeping events. Probabilities, being the dominant and most onerous part of the risk evaluation, combined with consequences, usually of economic and remotely of catastrophic nature, will provide important information for the navigational decisions of the ship master for a watch time ahead.

In the subsequent sections the concept of the so-called frequency domain approach of the ADOPT-DSS is presented, which is a probabilistic seakeeping assessment method suitable for onboard applications. It makes use of advanced methods of probability simulation and reliability theory, to deal with all kind of related uncertainties. Alternative probability methods like Monte Carlo, first and second order reliability methods FORM and SORM respectively have been explored. The method has been integrated within the ADOPT-DSS as an alternative to the time domain simulation method (see section 6) for the assessment of limit states with economic impact on ship operation.

The presented probabilistic seakeeping method has been successfully integrated in the risk-based DSS implementation at the Ship Design Laboratory of NTUA, Papatzanakis (2007). In this first implementation the two component codes have been interfaced, namely the seakeeping code for the deterministic calculation of the ship responses in specified seaway conditions and the probabilistic analysis program for the randomization of the conditions and the probability calculations.

5.2. Implementation

5.2.1. Seakeeping Code

The seakeeping code NEWDRIFT (*Papanikolaou,* 1989, 1992), has been used for the FDI implementation of the DSS. The code has been extensively validated in the past and provides multiple features that enable the modeling of a wide range of hazards. It is a 3D panel code for the calculation of the six degrees of freedom motions and loads of arbitrarily shaped floating or submerged bodies (like ships, floating structures, or underwater vehicles) at zero and nonzero forward speed. It enables the calculation of the first and the quasi second-order motions and wave–induced loads, including drift deviations, forces and moments. Finite or infinite water depth is assumed, and being excited by regular linear waves of arbitrary frequency and heading. Natural seaways are addressed too in the frame of linear spectral theory.

5.2.2. Probabilistic Program

For the probabilistic analysis the code PROBAN by *DNV* (2002) has been employed, which provides various methods for probability calculation and assessment, like Monte Carlo, First and Second Order Reliability Methods, FORM/SORM, manipulation of random variables and uncertainties and formulation of basic probabilistic problems. The code provides capabilities of interfacing to external software, like the seakeeping code of the present application.

5.2.3. Probabilistic Module

The interface structure of the seakeeping and the probability analysis codes for the operational mode is that shown in Figure 5-1 This corresponds to the Probabilistic Module as described in Figure 4-1 and provides a first level analysis of the internal structure.

Here each limit state has been defined as a separate sub-library under the probabilistic code PROBAN. Five different limit states have been implemented, which are evaluated with the spectral analysis tool “spectra” within the “scels” procedure. This latter procedure reads the Response Amplitude Operators (RAOs) as they are calculated by the seakeeping code NEWDRIFT. Once the RAOs have been calculated then the probability evaluation is carried out by running either once the Monte Carlo simulation or five times the FORM method once per limit state. The developed implementation is modular enabling the replacement of any limit state and the customization of DSS to every ship.

While this architecture has been proved efficient for the problem, the full automization could not possible at this level of development because of the use of commercial versions of the constituent software.

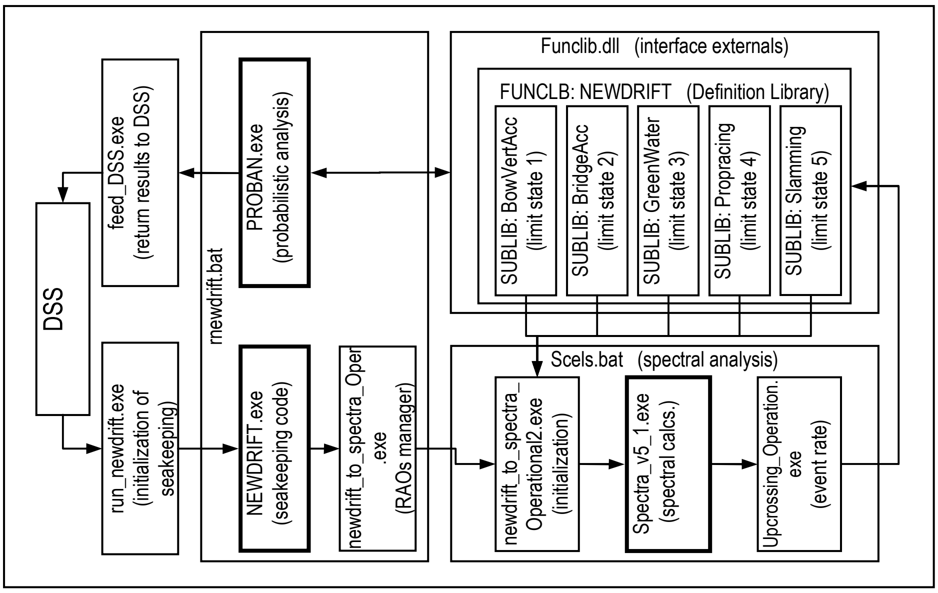


Figure 5-1 The structure of the probabilistic module in operational mode

5.2.4. Computational Performance

A fast computational performance in order to achieve practical application times onboard is a basic requirement set for the developed computer-based probabilistic approach. Although the computational time to complete a full set of calculations and evaluations strongly depends on the employed computer machine(s), the times recorded and provided herein enable a representative view of the current performance achieved at laboratory's environment.

With reference to a single PC computer, Intel Core2 CPU 6600 @ 2.40 GHz, 2 GB Ram and for a dense hull representation (2x500 panels) the computational times recorded were:
- 35 sec per Limit State evaluation, when using Monte Carlo
- 5 sec per Limit State evaluation, when using FORM

These are typical reference times of the DSS implementation; no optimization has been attempted so far, and standard computational hardware resources have been employed.

The recorded performance is better illustrated when consider an evaluation of the 5 limit states which takes 12.5 min to evaluate the total risk for 30 alternative sailing conditions. The results then cover a range of speed-heading combinations as shown in Figure 5-2 For this particular assessment the wave spectrum parameters have been assumed to be uncertain parameters.

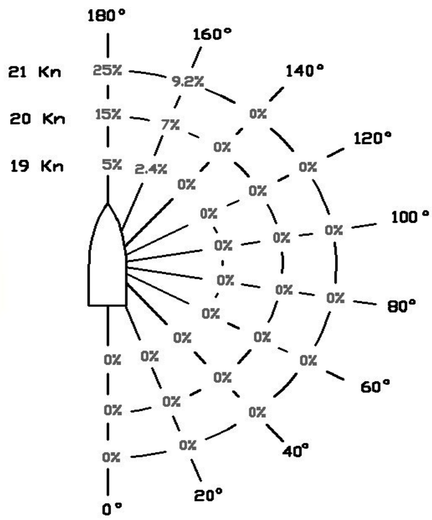


Figure 5-2 Probability for propeller emergence rate > (1 / min)

5.2.5. DSS Modes

The DSS is assumed for application to both ship operation and to a risk-based design procedure. Since it aims at ensuring lower risk levels in ship's operation correlated to a set of variables, the difference between the two modes for its use, namely design and operation, is the number of variables considered for each one.

In the operational mode the ship may be assumed as a time invariant system, namely her loading condition is assumed satisfactorily determined at the beginning of the trip. The parameters treated in this mode as random variables are the environmental parameters (wave height, period, etc.), while the risk controls are the speed, the heading, etc. Therefore at a certain time calling the DSS the ship loading is provided by ship's loadmaster software and the wave environment is measured by onboard instrumentation or best estimated by actualized forecasts; the DSS then searches for risk control options, namely alternative courses and speeds of lower risk (active risk measures).

In the design mode, substantially more variables are considered. Herein the ship loading, the forward speed, the wave heading and other characteristics, thus much more parameters are all assumed as random variables; they may be set by the ship designer to account for the long term (ship life) evaluation of risk to be achieved by use of the DSS. The decision in the design process is the mitigation of risk in ship life by use of design controls (passive risk measures).

5.3. Conclusions

A method for the onboard probabilistic assessment of the seakeeping of a ship subject to specific wave conditions has been introduced. The method has been specifically developed for application of risk-based navigational decision support systems DSS. The fundamental issues and properties have been discussed, while the necessity for an efficient probabilistic-seakeeping method in the core of the system has been highlighted.

The developed method has been successfully integrated within the ADOPT-DSS prototype. Validation studies with the prototype have proved the efficiency of the employed probabilistic method FORM (and SORM) for most considered limit states and for the operational mode of the developed DSS in which the randomness of waves is taken into account. For cases for which above methods prove less reliable, a Monte Carlo simulation should be also applied, ensuring the DSS system's reliability for the assessment of all envisaged operational conditions.

5.4. Needs for further development

The risk estimations by use of the *Frequency Domain Implementation* FDI obviously will depend on the data employed, like the uncertainty models of each parameter involved to the seakeeping problem and the assumed threshold values necessary for the definition of the hazard.

For example at the operational mode of DSS the ship loading conditions has been assumed to be well determined at the beginning of each voyage. Even in such case some uncertainty model could be still employed and the probabilistic analysis would be enhanced accordingly. Towards such development a dimensional analysis seems necessary to identify the parameters that affect the risk for each hazard in consideration. Then as the dominant factors of the hazards will be identified the appropriate probabilistic model connected to them should be searched.

In the current development of the DSS any hazards has been assumed to be defined as the excess of specific limits well known in advanced of risk assessment. Without such quantities the risk analysis remains inapplicable. In the development of the DSS the critical values as proposed in the literature have been used. Such data should be systematically refined and generate a referenced set of critical values for the hazardous sailing.

Further the probabilistic method the performance of the DSS depends on the employed hardware and the software for the prototype implementation. At this initial prototype application the system seems to perform close to the marginal limits of its practical application. Both seakeeping and probabilistic software need optimization and tailoring to the requirements of the DSS. An optimization of the performance of the DSS should be investigated with the aim to shift the design point of the system in more practical conditions characterized by appropriate redundancy for a system addressing the ship safety.

6. Numerical simulation – time domain implementation

Damages and losses due to large amplitude roll motions have become a governing problem of the shipbuilding and ship operating society. Although the phenomena which do actually lead to large amplitude roll motions in heavy weather are well known since more than 60 years, it is not so obvious that especially modern hull forms which are designed mainly for good propulsion efficiency and cargo intake actually favor the occurrence of large amplitude roll motions, because they are characterized by substantial alterations of the righting levers. To cope with this problem, numerical tools are available today which do allow calculation of the non linear behavior of the ship in heavy weather. The application of such methods in the ship design allows design of hull forms where this type of problem can be minimized. Besides, it is also possible to apply such kind of method with the aim of operational assistance, if these methods are used for on board decision support systems, provided, they are embedded into s suitable framework.
The ship response simulations in the ADOPT DSS were split into two parts: The linear responses, connected to economical losses, were treated by methodologies known from structural analysis. These methods are described in section 5, while the nonlinear responses, connected to safety, were treated by procedures described in this section.

6.1. Introduction

As a consequence of severe losses of cargo or even capsizes, there was a compelling need for the development of a decision support system which should assist the ship operators in avoiding critical situations. Within the framework of this decision support system, a strong focus was to be laid on the reliable prediction of large amplitude roll motions. In this context, the fact became obvious that there do exist some numerical tools that can actually cope with this type of problem, but these tools were typically used by specially trained people either in the academic field – mainly for experts during accident investigations or by some ship designers with the aim of improving the quality of the ship design. It became obvious that for on board applications, these type of methods requires too much specialist knowledge which impedes their application. And simply equipping these methods with a better user interface was not considered a reasonable way out of the problem.
During the long discussions in the ADOPT project to find the best system architecture for the ADOPT DSS, it became obvious that the above mentioned problem is embedded in other difficulties which needed to be solved for a practical DSS: Theoretically, it would have been possible to calculate a lot of information that would requires specialist knowledge beforehand. The for on board application could then make use of that pre- determined information and then interpolate in between for an actual scenario. However, this approach would have neglected the fact that practical sea states may be quite complex (e. g. 2 peak-spectra), which would then result in the fact that for reasons of minimizing computational effort as well as the amount of data, the description of the wavy surface had to simplified in such a way that the predicted results of such kind of DSS were considered as not good enough to really give reliable operational support. For these reasons, it was decided that the ADOPT DSS should have the capability of calculating the actual ship response directly on board for a specific situation, which is given by a actual representation of the sea state as well as by the actual speed, heading, course etc.
This demand required calculation procedures that have sufficient response tomes to cope with this demand as well as sufficient robustness to avoid incorrect results, which may be computed on the basis of insufficient input data or because the underlying theory is

overstressed. This resulted in the fact that the actual architecture of the ADOPT DSS needed to split into the following modes of application:

- **Design mode**: During the design mode, the ADOPT DSS shall identify all risks related to operations in heavy weather, and all design measures to improve the sea keeping behavior of the ship may be seen as risk control options. The application in the design mode shall be done in the design system of the shipyard to get all necessary data as well as to make use of the available design control options. The application during the design mode is done by shipyard specialists, and all necessary know-how to better understand the specific ship responses of that particular ship design are generated. However, this application requires the possibility of quantitatively measuring the actual risk to identify the best risk control options. As a prototype installation, the ship design system E4 has been chosen.
- **Training mode**: Based on the information already achieved during the design mode, the DSS shall now be used in the design environment for training purposes. The training is intended for the crew to better understand the specific behavior of their ship, and based on the training mode, an operational manual is developed that will inform the crew on the general behavior of their ship in selected situations. The training mode also allows for introducing some core elements of the theory to the crew. Risk control options may be the proper adjustment of load cases or other operational measures such as pre trim or other.
- **Operational mode**: The operational mode will result in an on board installation of the DSS which is a subset of the design and training installation together with the ship data base. The on board installation will sense the sea state and the operational parameters of the ship and it will calculate the ship reaction and the related risks automatically.

During the development of the DSS which should be a risk based DSS including the uncertainties, it became clear that especially the strongly non linear character of the ship roll motion made it impossible to combine the motion analysis with the risk computing procedures that could successfully be applied for the linear motions. The combination of FORM/SORM as implemented in PROBAN with the sea keeping failed for this high non linear type of problem. The main reason identified for this is that the search algorithm for the so called design point implemented in PROBAN has problems in handling high non linear system responses with discontinuities like the capsize problem.
This is not only a problem of the search algorithm, but of FORM/SORM in general. This posed the problem to develop a procedure for calculating failure probabilities for strongly non linear problems within the framework of the ADOPT DSS for all three modes of operation. And this demand resulted in the fact that the response part of the ADOPT DSS was split into two parts: The linear responses were connected to economical losses, and they are treated by methodologies already known from structural analysis. The non linear responses on the other hand are connected with safety relevant problems which are associated with severe consequences. These types of problems are treated by procedures described in this paper.

For the design mode, a new concept was introduced called Insufficient Stability Event Index {ISEI} based on a large database of ships simulated in various sea states. An introduction to this new approach is given below. As the computational effort for the ISEI is still beyond the scope of the operational mode, a concept of determining probabilities of rare events was implemented for the operational mode which allows computation of realistic failure probabilities of rare events in artificially increased wave heights.

The elements of this concept are validated for some full scale stability accidents, where a rare event has actually occurred.

6.2. E4- ROLLS Simulation Tool

The simulation code E4-ROLLS, based on the code developed by Kroeger (1987) and Petey (1988), was chosen to serve as basis for the prediction of the ship motions in heavy weather within the ADOPT DSS framework.. The code was validated and further enhanced by Cramer and Krueger (2005). The code considers all six degrees of freedom, whereas only two of them, namely roll and surge, are treated non-linearly. All others are calculated by transfer functions, which makes the code extremely fast. This enables us to calculate relatively long time series for a vast number of variations. As the code is able to predict abt.20000s real time in abt. 5 seconds on a typical PC, E4-ROLLS is fast enough to allow for on board computations within the ADOPT DSS framework.

The roll motion is simulated using equation [6-1].

$$\ddot{\varphi} = \left\{ \begin{array}{l} \sum M_{wind} + M_{sy} + M_{wave} + M_{Tank} - M_d - \\ m(g - \ddot{\zeta})h_s - I_{xz}\left[\left(\ddot{\vartheta} + \vartheta\dot{\varphi}^2\right)\sin\varphi - \left(\ddot{\psi} + \psi\dot{\varphi}^2\right)\cos\varphi\right] \end{array} \right\} / \; I_{xx} - I_{xz}\left(\psi\sin\varphi + \vartheta\cos\varphi\right) \quad [6\text{-}1]$$

with

M_{wind}	Moment due to wind
M_{sy}	Moment due to sway and yaw motion
M_{wave}	Moments from radiation, diffraction and Froude-Krylow forces
M_{Tank}	Fluid shifting moment
M_d	Non-linear damping moment
φ, ϑ, ψ	Roll, pitch and yaw angle
m	Ship's mass
$\ddot{\zeta}$	Heave acceleration
h_s	Righting lever
I_{xx}, I_{xz}	Roll moment of inertia and mixed part

The current righting levers are determined by applying Grim's equivalent-wave concept as modified by Soeding (1982). This approach replaces the exact wave contour along the ship's hull by a simplified wave profile, which delivers similar righting levers as the exact solution. The coefficients of the equivalent wave are determined using a least squares approach.
Leaks and tanks can be taken into account as well for more detailed investigations. For this method the geometry of the respective tanks needs to be modelled. Once the geometry is known, the fluid movement within the tank can be calculated, using either a deep-water model or a shallow-water model depending on the tank's eigenfrequency. The deep-water model treats the water as a point mass concentrated in its current centre of gravity, assuming that the water surface is always an even plane. The shallow-water water model is implemented according to Petey (1985). A typical application of E4-ROLLS during an accident investigation is shown in Figure 6-1. The red curve shows the roll angle of the ship, which reaches 40 degree in a following sea scenario. The black and blue curves show the amount of water that enters or leaves the space between bulwark and hatches.

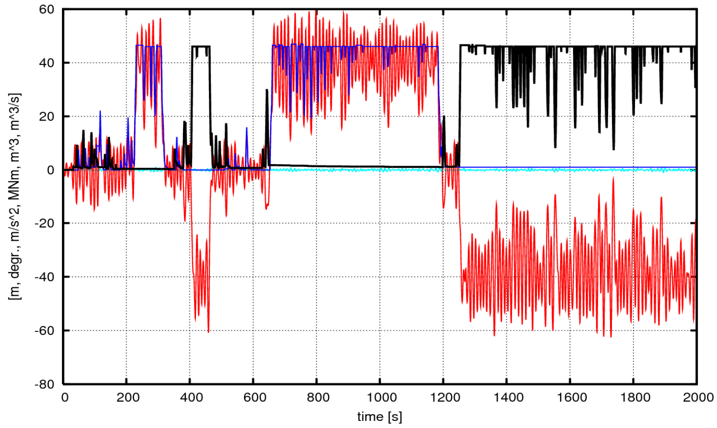


Figure 6-1: Example of a time series obtained with E4-ROLLS for a capsizing incident of a small coaster.

6.3. Failure Criteria

6.3.1. General

To serve the demand of a risk based DSS, it is required to define possible failure criteria that will allow computation of the probability of failure in connection with large amplitude roll motions. These failures can be associated to a e.g. threshold roll angle, which may be most useful for the operational mode of the DSS. But we should keep in mind that we want to predict probabilities for extremely rare events, and during the operational mode, we deal with a short term problem, whereas for the design and training mode, we want to evaluate a design based on long term statistics. This must result in different failure criteria for the different tasks. The following sections introduce some failure criteria and procedures which were implemented into the ADOPT DSS framework for non linear roll motions.

6.3.2. Soeding's Concept of Simulating Rare Events by Artificially Amplified Wave Heights:

As demonstrated in Figure 6-1, E4-ROLLS delivers time series of the ship motions in a random sea state. Therefore, the related probabilities of an event, e.g. the occurrence of a threshold roll angle, can in principle be determined by simply counting the up crossing rate of that event. If, e.g. during a simulation of 20000s, 20 capsize events are counted, then the related capsizing rate would simply amount to 20/20000 = 1.E-3. And, as E4ROLLS is fast enough to generate a sufficient amount of time series where each time series covers a sufficiently long enough time span, this procedure is feasible. So it is easily possible to determine the related probability and the risk connected to that probability, provided, there are enough events to actually count. But, as extreme events (e.g. capsizing) are extremely rare (or at least should be), it is difficult to determine significant values for capsizing probabilities during model tests and numerical simulations due to the limited duration and the resulting small number of occurrences. This is simply due to the fact that in typical operational conditions, the occurrence of such events is very seldom and there are simply not enough events to count. And, even a very long simulation time can not guarantee that no dangerous event will actually occur due to the random nature of the process as such. Consequently, we need to find a procedure where we can theoretically increase the occurrence of such kind of events.

Therefore, Söding and Tonguc (1986) suggested simulations in artificially higher waves. By assuming Rayleigh-distributed amplitudes, the capsizing probability can be extrapolated to the actual wave height of interest if simulations in artificially higher waves are performed by the following relationship:

$$\frac{H_{sim}^2}{H_{act}^2} = \frac{\ln(p_{sim}) + 1.25}{\ln(p_{act}) + 1.25} \quad [6\text{-}2]$$

In equation 6-2, H denotes the limiting significant wave heights either of the actual situation of interest (denoted by act) or of the artificially increased wave height during the simulation (denoted by sim). P denotes the related probabilities. This concept results in a simple procedure to be applied for the determination of probabilities: For a given situation by a sea state (assumed as irregular, but with respect to the governing parameters like significant period or height as stationary), speed, heading and loading conditions, simulations are performed which do use exactly these parameters except for the significant wave height. The latter is increased until a reasonable number of events of interest is obtained during the simulations. These can then be counted and using equation 6-2, the probability obtained from the simulations can be extrapolated to the wave height of interest. The concept is traigh forward, robust and therefore easy to automate. It was found to be useful for the operational mode of the DSS to compute the failure probability for a given situation. The disadvantage of this concept is related to the fact that there is a slight dependency of the computed failure probabilities on the actual selection of the significant wave height amplification ratio. This results in the problem that if during the design mode application, small alterations of the design are carried out, these are not well reflected by the related probabilities. So it is possible that a small increase of stability, which may be a typical situation during the identification of allowable GMs, results in a slight increase of the computed failure probability, which makes it hardly possible to identify e.g. stability limit curves. Therefore, fore the long term evaluation during the design mode of the ADOPT DSS, other procedures must be implemented which do better serve the design aspect and the related risk control options.

6.3.3. The Blume Criterion of the residual area

Blume/Hattendorf (1987) developed this criterion to evaluate the ship safety with respect to capsizing in following and stern quartering seas by model tests. For each run during the model test the maximum roll angle was registered. Then the residual area E_R below the still water lever arm was calculated, limited by the maximum roll angle and the point of vanishing stability (see Figure 6-2.). If the ship capsized during the run, E_R is set to zero. Finally a ship was regarded as safe against capsizing if it fulfills the following requirement:

$$\overline{E}_R - 3s > 0 \quad [6\text{-}3]$$

Here $\overline{E}_R$ denotes the residual area averaged by all runs, *s* represents the standard deviation of E_R. By this a stability limit, represented by either a minimum GM or by a limiting maximum wave height can be determined.

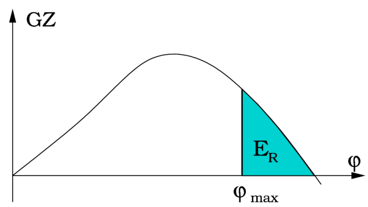


Figure 6-2: Concept of the Blume- Criterion related to the residual area under the still water righting lever curve from a maximum roll angle obtained during a model test until the point of vanishing stability.

This concept is useful for the application during the design mode of the ADOPT DSS. Because it offers a straight forward, robust way to generally distinguish a situation between safe or unsafe. As it is based on the still-water stability curve, small changes in stability or other related design parameters are correctly reflected. Practically, this criterion can be implemented in such a way that for a given ship condition and sea state, a limiting significant wave height can be determined where the ship hardly fulfills the Blume criterion. To do so, a sufficient number of simulations are performed and the maximum roll angle during the individual simulations can be determined. Then, the residual areas as well as the standard deviation can be calculated. Iteratively repeating this procedure a limiting significant wave height can be determined which hardly fulfills equation 6-3. During the design mode application, design modifications can be identified that lead to an improvement of the design, which is expressed by larger significant wave height the ship can survive.

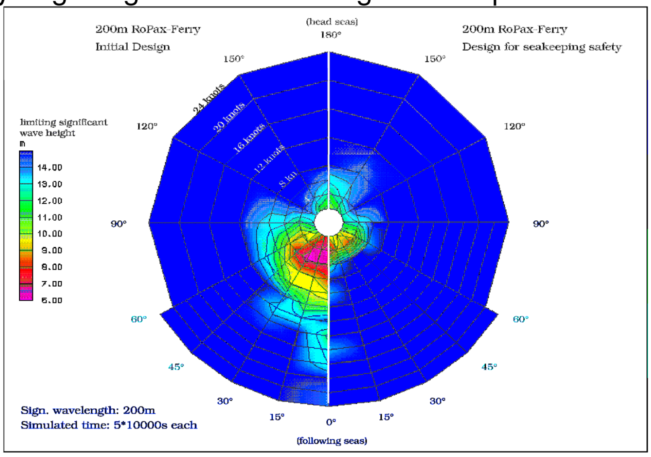


Figure 6-3 : Example of a polar diagram computed with E4-ROLLS for the limiting significant wave heights for a given significant period T1 which fulfill the Blume Criterion. The radial axis denotes the ship speed, the circumferential axis the encounter angle. Left: A typical RoRo-ferry with pronounced 2:1 and 1.1 resonances in following seas. Right: Improved design by modified hull form and stability as risk control option.

The disadvantage of the application of the Blume-Criterion is the fact that it simply distinguishes a specific situation (which may represent a short term situation) between safe and unsafe, and it does not quantify the related probability. Further, a disadvantage of the Blume Criterion can be seen in the fact that it may disregard the extreme rarity of the events of interest, because it makes no use of the concept of the simulation in artificially higher waves. However, the latter can be compensated if also sea states which larger significant wave heights as practically possible are taken into account. And, from a long term point of view, failures in situations that do extremely seldom occur may be tolerable with respect to the ship design. Nevertheless, an additional concept is required to better quantitatively compute the long term failure probability during the design mode of the ADOPT DSS.

6.3.4. The Insufficient Stability Event Index (ISEI)

After some incidents related to parametric rolling with container vessels become known at the end of the last decade, a German research group was established to develop dynamic stability criteria, which should be based on numerical simulations. A research program was established in which a large number of model tests for different modern hull forms were carried out with tailored wave sequences to validate the simulation code E4ROLLS. It was concluded that the simulation code was able to predict all relevant phenomena related to the problem of insufficient stability in waves with sufficient accuracy. Therefore, it was decided to develop a concept for minimum stability based exclusively on numerical motion simulations. Based on the numerical simulations, the following main findings were made or confirmed:

- Both model tests and simulations confirmed that critical situations endangering the ship with respect to large roll amplitudes are observed in head as well as following seas.
- No capsizing events were found in beam seas at zero speed.
- The most dangerous scenarios appeared to be those where the ship was traveling in following and stern quartering seas.
- In head and head-quartering seas, large rolling angles were observed, but capsizing usually did not occur. This is due to the fact that critical resonances are connected to relatively low values of GM in following seas, and to high GM values in head seas. The model tests were conducted close to potentially critical resonances.

Unlike the expectations by previous authors, wavelengths significantly shorter than the ship length could endanger the vessel, whereas wavelengths significantly larger than ship length did not initiate large roll amplitudes.

In contradiction to previous criteria, it was decided to determine all possible scenarios that may lead to a dangerous situation, but not to quantify just how dangerous a specific situation actually is. When defining limiting stability values, it is of importance to assess the probability of a specific loading condition being dangerous or not for the vessel. For this application it is not of practical interest to get the exact capsizing rate during the simulation, but it is singularly important to know if the ship did fail. Based on this, the concept is aimed towards determining long-term probabilities rather short-term probabilities. Thus, the concept requires a methodology to distinguish between being safe or unsafe for a ship in a specific situation without counting the actual up-crossing rates.

Given that such a methodology is available, the total long term probability for a dangerous situation happening in a specific loading condition can be defined, then by the insufficient stability event index (ISEI), which is defined by the following equation (see also Krueger and Kluwe (2006)):

$$ISEI = \int_{T_1=0}^{\infty} \int_{H_{1/3}=0}^{\infty} \int_{\mu=0}^{2\pi} \int_{v_s=v_{\min}}^{v_{\max}} p_{sea}(H_{1/3}, T_1) \cdot p_{dang}(H_{1/3}, T_1, \mu, v_s)\, dv_s\, d\mu\, dH_{1/3}\, dT_1 \quad [6\text{-}4]$$

Here p_{sea} denotes the probability of occurrence of a specific sea state defined by the significant wave height $H_{1/3}$ and the characteristic (peak) period T_1, whereas p_{dang} represents the probability for the actual loading condition leading to a dangerous situation under the condition of a specific sea state.

The two-dimensional probability density function is calculated from a scatter table presented by Soeding (2001). Taking the discrete values from the scatter table for each of the intervals for $H_{1/3}$ and T_1, the integration of equation [6-4] can easily be transformed into a summation of the respective values.

The probability that the actual loading condition leads to a dangerous situation in the sea state given by $H_{1/3}$ and T_1 then can be written as follows:

$$p_{dang}(H_{1/3}, T_1, \mu, v_s) = p_{fail}(H_{1/3}, T_1, \mu, v_s) \cdot p_{\mu}(\mu) \cdot p_v(v_s | H_{1/3}, T_1, \mu) \quad [6\text{-}5]$$

In this equation, $p_\mu(\mu)$ denotes the probability the ship is traveling at a course of μ-degrees relative to the dominating wave propagation. It is assumed that $p_\mu(\mu)$ is independent from the actual values of $H_{1/3}$ and T_1. $p_\mu(\mu)$ can be taken from full-scale observations (see Krueger, Hinrichs, Kluve and Billerbeck (2006)). Then $p_v(H_{1/3},T_1,\mu,v_s)$ denotes the probability that the ship is traveling at a speed of v_s knots. As $p_\mu(\mu)$ is selected independently from the seastate, $p_v(,v_s/H_{1/3},T_1,\mu)$ is a conditional probability depending on all four parameters, as not all speeds are physically possible in a specific situation. Krueger, Hinrichs, Kluve and Billerbeck (2006) determine the maximum possible ship speed in the given environmental conditions at full engine output and the minimum speed at engine idle speed from systematic propulsion calculations. Within the range of possible speeds $[v_{min},v_{max}]$ the probability of occurrence is assumed equally distributed as more accurate data is lacking.

The failure probability $p_{fail}(H_{1/3},T_1,\mu,v_s)$ is determined from the time series of the numerical simulation by applying the Blume-criterion mentioned above. Given the loading condition fulfills the Blume-Criterion in the actual situation, $p_{fail}(H_{1/3},T_1,\mu,v_s)$ is set to 0, which means that the loading condition is sufficiently safe for the given conditions. In case the Blume-criterion fails for the current situation, $p_{fail}(H_{1/3},T_1,\mu,v_s)$ is set to 1. This equation means that decision is taken only between “safe” and “unsafe” by setting the failure probability to 0 or 1, respectively.

All situations in which the failure criterion is set to 1 contribute to the overall long-term probability. Formally this does not deliver a correct capsizing probability, which is the reason that the result is called “capsizing index.” Yet taking into account the practical considerations, it seems to be more important for us to identify dangerous situations than to determine the exact failure rate in a specific situation that is known to be dangerous.

Furthermore, it should be noted that our method explicitly treats head sea and following sea cases only. Therefore, we restrict the contributing courses to a 45-degree sector of encounter angles, port and starboard in head and following seas. Consequently, it is then useful to split the ISEI in a head sea and a following sea index. The ISEI then can be written as follows:

$$\begin{aligned} ISEI &= ISEI_{following} + ISEI_{head} \\ &= \sum_{i=1}^{N_{T_1}} \sum_{j=j_{Bl}}^{N_{H_{1/3}}} \sum_{k=1}^{N_{\mu,f}} \sum_{l=1}^{N_{v,f}} p_{sea}(H_{1/3}(j),T_1(i)) \cdot \\ &\qquad p_\mu(\mu(k)) \cdot \\ &\qquad p_v(v(l)|H_{1/3}(j),T_1(i),\mu(k)) \\ &+ \sum_{i=1}^{N_{T_1}} \sum_{j=j_{Bl}}^{N_{H_{1/3}}} \sum_{k=1}^{N_{\mu,h}} \sum_{l=1}^{N_{v,h}} p_{sea}(H_{1/3}(j),T_1(i)) \cdot \\ &\qquad p_\mu(\mu(k)) \cdot \\ &\qquad p_v(v(l)|H_{1/3}(j),T_1(i),\mu(k)) \end{aligned} \qquad [6\text{-}6]$$

In the formula, the summation on the limiting wave heights starts at j_{Bl}, which is the smallest significant wave height for the given significant period T_1 where p_{fail} equals 1. The encounter angles run from $\mu=-\pi/4$ to $\mu=+\pi/4$ for the following sea cases and from $\mu=3/4\,\pi$ to $\mu=5/4\,\pi$ for head seas. The speed summation runs from the minimum speed possible in that condition to the maximum speed possible. The indices *h* and *f* indicate head and following seas, respectively.

For practical applications, it is useful to find those combinations of $H_{1/3}$, T_1, μ and v_s, which represent the limit between “safe” and “unsafe.” This solution can be most efficiently achieved by finding the limiting significant wave height for a given combination of parameters T_1, μ and v_s according to the Blume-criterion. In cases where the Blume-criterion does not deliver suitable results typically due to large angles of vanishing stability, the occurrence of a

certain maximum roll angle may be simultaneously taken into account.. The more conservative value is taken for the decision between “safe” and “unsafe.” The results may be plotted in the form of polar diagrams as presented in 3. Each polar diagram presents the limiting wave heights for a specific significant period (or the related significant deep water wave length), giving an overview about critical situations (see Cramer and Krueger (2005) and (Krueger 2002). Typically the simulations, with a duration of 20000 seconds in real time, are repeated five times, each with different wave realizations.
The ISEI-concept allows the identification of ship designs and ship types, which are vulnerable for insufficient stability events in following or head seas. At this, the ISEI-concept takes into account all relevant phenomena occurring in head and following seas that may endanger the vessel with respect to minimum stability. Unfortunately, there is no limiting value for the ISEI thus far making it difficult to actually apply the concept with respect to the determination of minimum stability requirements. In order to define threshold values for the ISEI-concept, Krueger and Kluwe (2006) suggested analyzing the safety levels for a large number of existing ships by using the ISEI as the quantitative measurement.

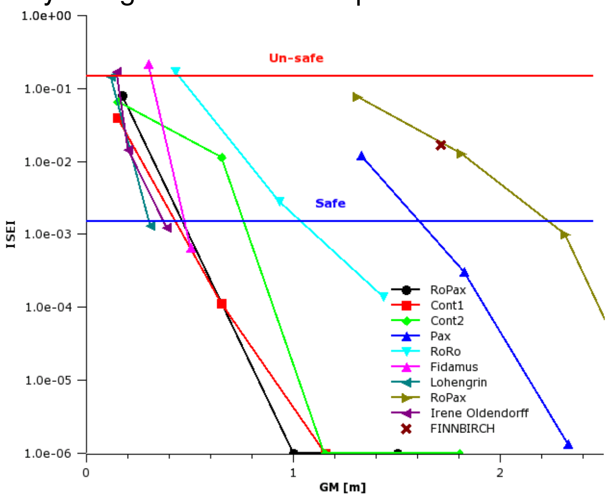


Figure 6-4: ISEI- values computed for different ships including some real full scale stability accidents.

Therefore, many full scale capsizing events have been analyzed with the a. m. procedure and the resulting ISEI- values have been computed. As the ships did actually capsize, it was then straight forward to identify ISEI-values which will definitively lead to a long term failure. For the DSS design mode application, this results in the fact that if for a given ship design, a critical ISEI value is calculated, this should result in design modifications, which are typically the limiting minimum GM curves. During our analysis of several stability accidents, we benchmarked the accidents against several stability criteria (either empirical or theoretical ones) published by different sources, and we found that mostly all criteria converged in judging a specific ship as being safe. For this condition, we have again computed the related ISEI value, and, following this procedure, the following results were obtained:

- An ISEI value below 1.E-3 represents a ship design and loading condition where the long term occurrence of a safety related stability event due to insufficient stability is extremely unlikely.
- An ISEI- Value of abt. 0.05 or more represents a ship design and/or loading condition where it is extremely likely that a severe stability event will occur.
- ISEI-values between 0.05 and 1.E-3 represent intermediate conditions, where a severe stability event may happen with reasonable probability.
- So the ISEI concept can be used to support the design sand training mode in a reasonable way, as it is possible to quantify the risk related to large amplitude rolling.

If for a specific design and load case ISEI values below 1.E-3 are calculated, the design should be reviewed accordingly. During the training phase, risk control options can be identified which ensure an ISEI-level well below that threshold value. As the ISEI implies that there will be some situations where a large rolling angle event may occur, these situations can be identified during the operational mode of the DSS and the crew can be informed accordingly.

6.4. Application example: The FINNBIRCH accident

6.4.1. Background of the Accident

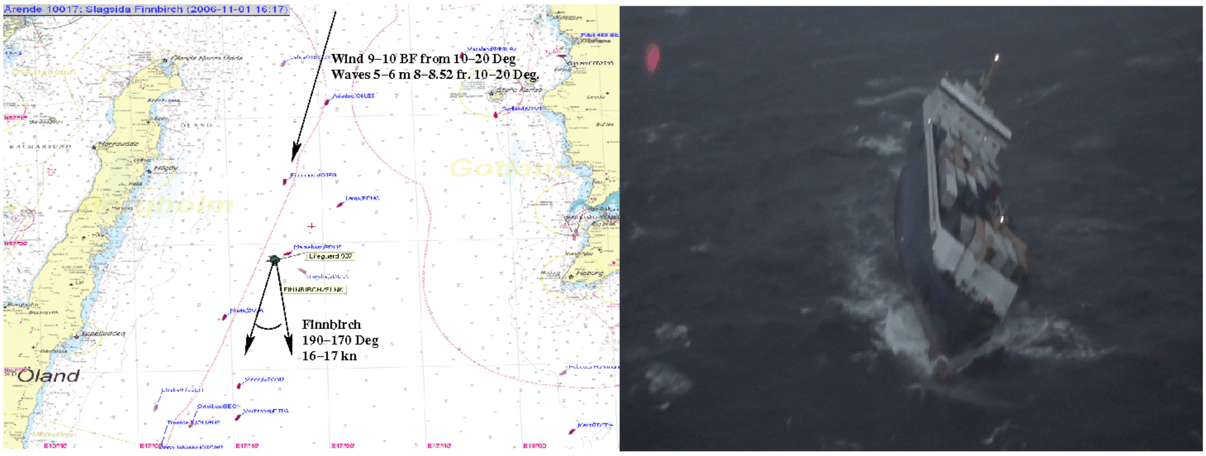


Figure 6-5: Accident scenario (left) and the final floating condition of the MV FINNBIRCH after the accident.

The tools for predicting large amplitude roll motions are validated for a recent accident which took place in the Baltic sea. On Wednesday, 1st of November 2006, the 8500 dwt RoRo-Ferry MV FINNBIRCH capsized in heavy weather in the Baltic Sea between the islands Gothland and Oland. At the time of the accident, the vessel was travelling south at an estimated course of abt. 170- 190 Degree, speed about 16- 17 knots. The vessel was bound for Aarhus with a cargo of RoRo- Trailers, where a significant amount was stowed on the top deck (see Figure 6-5, right). During the time of the accident, the weather was rough with wind forces of 20-25m/s or BF9-10. The sea was also rough with significant wave heights of abt. 5-6 m, significant period about 8-8.5 s from NNE to NNW.
According to the observations of the MASTER of MV MARNEBORG, the vessel closest to the MV FINNBIRCH which coordinated the rescue operations later (we refer to an interview the master of M/V MARNEBORG gave to the Swedish paper Aftonbladed on 03.11.2006). MV FINNBIRCH was rolling significantly in the rough seas and at about 16.15 hrs, she heeled to about 50 degree. The vessel remained for a while in that intermediate equilibrium floating condition, until she finally capsized at 19.37 hrs. The final position of the vessel is reported as 57 Deg. 08 Min. N, 18 Deg. 32 Min. E. Except of two lives, the crew could be rescued. The wreck could later be found in a water depth of about 80 m by sonar operations. The map shown in Figure 6-5, left, (the map was derived based on the internet publication of the Swedish Sjofartsverket.) summarizes the capsizing accident. The vessel M/V FINNBIRCH (call sign SLNK) was built in 1978 by Hyundai as M/V Stena Prosper, Yard no. 646, and has been converted several times since its delivery.

Later in 1979, the vessel was additionally equipped with side sponsons. These sponsons were fitted to increase the stability, as the vessel should carry containers in at least two tiers on the upper deck. Later, in 1986, the vessel was retrofitted with an additional top deck (4th trailer deck) and was then able to carry trailers on four decks. This conversions has significantly affected the design and operational performance of the vessel, as the following application of the ADOPT DSS will show.

When MV FINNBIRCH was delivered in 1979, no damage stability regulations were in force, which means that the stability of the vessel was governed by the relevant intact criteria. The same situation also holds for the conversions. This explains the reason for the relatively low minimum freeboard of abt. 0.4 m if the vessel is loaded down to the extreme draft. Astonishingly, the side sponsons were already fitted shortly after delivery. The reason was most probably that the vessel should carry containers in at least two tiers on the upper deck. According to our calculations which are based on the original hull lines, the additional sponsons resulted in additional buoyancy of about 200 tons at the extreme draft. The sponsons allowed for an increase of permissible VCG of about 0.45m, see below. When the vessel was delivered without sponsons, the limiting intact stability criterion were (according to our calculations) the requirement for 0.2 m righting lever at 30 degree for the larger drafts and the area requirement to 30 degree at the smaller drafts. As the windage area of the vessel was quite small, the weather criterion resulted in limiting KG values which were above these requirements. According to our calculations, the sponsons were designed in such a way that the weather criterion, which resulted in higher requirements now for the increased windage area due to the top deck, was still not the limiting criterion, but the vessel's stability including the sponsons is still determined by the 0.20m righting lever requirement at 30 Degree. Due to the fitting of the sponsons, the increase in permissible VCG resulted to 0.45 m compared to the original design without sponsons. Righting levers computed for the vessel in a wave like for the accident scenario (Figure 6-6, left) shows that the vessel has practically not residual stability on the wave crest, which is the main source for the large roll angle. The stability loss is in close connection with the conversion.

6.4.2. Validation of the ADOPT DSS operational mode, Mode 1

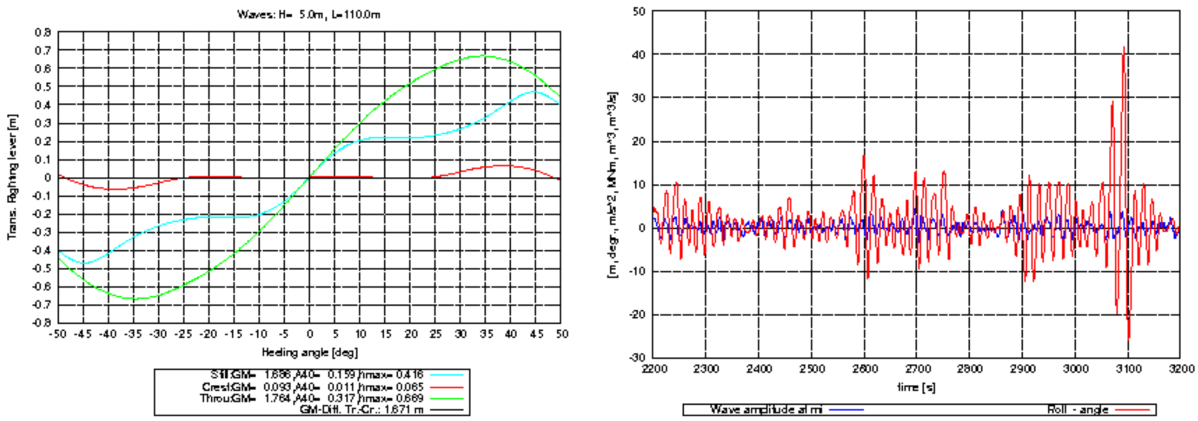


Figure 6-6 Righting levers of MV FINNBIRCH during the accident for Stillwater, crest and trough (left) and time series obtained from the E4ROLLS implementation. Note that during the simulation, the vessel easily reaches roll angles beyond 40 degree in the accident situation, because the stability on the wave crest is insufficient.

As a first validation check, it was analyzed whether the operational mode of the ADOPT DSS would have identified the situation as dangerous. A simulation model was set up based on the load case and light ship weight data. The simulations have clearly shown that in this specific situation, extremely large roll angles will occur that will most probably lead to the loss of the ship. In 65 from 100 simulations of 10.000 seconds each, the vessel capsized one or more times. The average capsize rate was determined to abt. 0.72per simulation, which resulted in an average capsizing period of 13888 s or 38.6h. It is quite obvious that this value is absolutely intolerable. Interesting to note, it was not necessary to perform the simulations in artificially amplified limiting significant wave heights, as already the actual significant wave height resulted in sufficient events to count. This clearly shows that the operational ADOPT DSS application would have identified this situation as extremely dangerous, and the crew would have been warned correctly.

6.4.3. Validation of the ADOPT DSS training mode, Mode 2

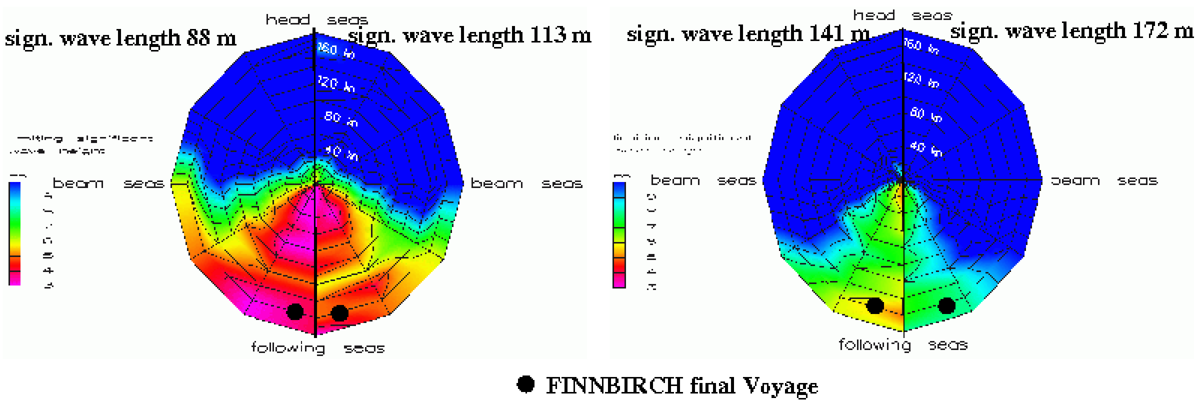


Figure 6-7 : Polar Diagrams with limiting significant wave heights according to the Blume Criterion during the simulated ADOPT DSS training environment. The limiting significant wave heights were computed for different significant wave lengths from 88 to 172 m. The accident wave length was about 113 m.

To simulate the training mode of the ADOPT DSS, it was assumed that the accident loading situation was equivalent with a design load case that may have been part of the stability booklet. For this load case, several polar diagrams were calculated which do fulfill the Blume-criterion. Some of the results are plotted in Figure 6-8 and they may serve as examples on the information that can be obtained by the ADOPT training DSS. All polar diagrams indicate that the ship clearly has a problem in following seas, especially at higher speeds and steeper waves. So the crew can be advised the following during the training mode: For this specific load case, in heavy weather, all following sea courses should be avoided unless the significant wave height and significant wave length are known with sufficient accuracy. For the longer waves, it might be possible to sail stern quartering courses if the stability is known with sufficient accuracy. For the accident situation (left polar diagram, right side) a slight alteration of course or speed would not help the vessel to escape from that situation. It would be a good advice to the crew not to start the voyage with this loading condition if heavy weather is expected. Additional water ballast is in fact required. The fact that longer waves lead to less critical situations can be explained by the fact that the righting lever alterations become less severe (although the right polar diagram, left side represents the case where the significant wave length equals ship length) and that critical resonances are shifted to less problematic speeds. Because it can clearly be seen in the left polar diagram that the vessel suffers additionally from the strong domination of the 2:1 roll resonance (at about 6 knots) and the 1:1 resonance (at about 16 knots). This phenomenon is in so far very interesting, as it clearly demonstrates that a linear estimation of a dangerous situation completely fails for this case: If the natural roll response period of the ship is determined based on the GM of the Stillwater curve, the 1:1 resonance would be computed for a speed of 9kn in following seas, whereas the 2:1 resonance should not even exist in following seas. It is quite clear that one can not obtain reliable results by a theory which linearizes the problem with respect to the still water righting lever curve for small angles, see also Figure 6-7, left. This clear shows the demand for the correct non linear treatment of the rolling motion within the ADOPT DSS framework. And the application also shows that during the training mode of the DSS, the crew could have been informed in general that the loading condition is not very favorable and should be improved.

6.4.4. Validation of the ADOPT DSS design mode, Mode 3

To demonstrate the principal feasibility of the ADOPT DSS support in the design phase, the ISEI was computed for the given loading situation (see also Figure 6-4). The computations resulted in an ISEI value of 0.06 which clearly indicates that them ship will be exposed to an insufficient stability problem after the conversion. So it was a design option to increase the stability of the ship until the ISEI value was sufficient, which resulted in a VCG shift of abt. 20 cm downwards. This resulted than in an ISEI value of 3.0E-04. So the vessel would have most probably survived the situation if the design had foreseen about 20cm more stability. Interesting enough, this amounts to roughly half the value the of the possible VCG shift after the retrofitting, and this is reasonable, because the vessel has operated for more than 10 years in the original condition without a capsize. This shows that the ADOPT DSS would have helped to identify a possible risk in the future operation after the conversion, which was not identified by the existing stability rules.

6.5. Conclusions and needs for further development

A procedure was presented that can serve within the ADOPT DSS framework as a prediction tool for large amplitude roll motions. Several failure criteria were introduced, which can serve the different application modes of the ADOPT DSS, namely design mode, operational mode and training mode. The core of the emotion analyzer is the simulation code E4ROLLS, which is fast and robust enough to generate time series on the ship motions in heavy weather. The procedures defined for the DSS were tested for some full scale accidents, where one application was demonstrated in this paper. The results show that the accident could have been avoided if a DSS would have been applied either in the design, training or the operational phase of the ship.

Nevertheless, there is still space for further developments. The uncertainty control has to be improved in the time domain implementation. Either a better uncertainty handling has to be implemented in the code or the magnitude of the uncertainties has to be reduced. Here, especially the uncertainty of the loading data has to be named.

Another aspect is that the hazard "loss of course control" is not implemented in the current system. This hazard has to be handled in the time domain due to the high nonlinearity also.

7. Man-Machine Interface

7.1. Introduction

The overall objective for the Man-Machine-Interface (MMI) is to display the information for decision making as received from the respective modes of the different decision support kernels. Due attention has to be paid to:

(1) What are the expectations of seafarers on DSS?
(2) Present the data clearly and customized to the task in order to avoid misunderstandings
(3) Allow for an easy "navigation" within the display and menus
(4) To enable some customization regarding the kind of results and the "look and feel", while keeping the system straight forward and basic (no fancy buttons and menus for confusion)
(5) To support the user to leave or avoid potentially dangerous situations in ship operation without entering the next one
(6) Identify and define appropriate connections to existing systems already available on the bridge

7.2. Generic Layout of the Man-Machine-Interface

In the development of the Man-Machine-Interface the focus was laid on the operation and training mode. In a design environment the naval architects use many different tools with which they are very familiar thus developing new interfaces for the design mode would have been of little gain. Thus the user group could have been narrowed down to ship masters and nautical officers.

The operation mode will usually be characterized by an application of the system in a real-time environment, with a rough sea and heavy ship-motions. In such situations the ship masters would need a system which clearly indicates the risk of the current situation and the possibilities to reduce that risk. Their interest on additional information is only second-rated and depends very much on the personality of the user. On the other hand, consistency is a very important aspect for the acceptance of a system. Due to this reason the provision of additional information explaining the results of the system is a crucial part of the system. Thus, one of the overall aims should be to provide comprehensive options to adapt the system to the specific user needs.

7.2.1. Structure of the Man-Machine-Interface

When structuring the MMI it had to be taken into account that the users become acquainted with the DSS in the training mode. There they will have to develop an understanding of the theoretical background of the DSS and establish their confidence in the system and its reliability. Under the consideration of consolidating the learning matter it is of high importance to enable the access to the training mode information also in the operation mode. Therefore, in terms of consistency, it will be necessary that besides giving information on the risk situation and decision support the additional information on how the risk has been calculated should also be made available. Taking this into account the MMI should consist of different units presenting the following information:

- **Overall risk**: including the main additional information
- **Overview on limit states**: displaying the status of all limit states on one screen
- **Risk of single limit state**: providing the information and data for each single limit state
- **Modules**: comprehensive collection of all data fed into the different ADOPT-Modules, including their actual values

As the four units provide increasingly detailed data it would be reasonable to structure the MMI in a hierarchical way (Figure 7-1). This means, that the unit overall risk would be the first screen to be presented, giving the main information as soon as the program has been started. Users who are looking for more detailed information would need to dig deeper into the program. For the most detailed degree of information, it might be useful to offer the users the possibility to choose by themselves if they would prefer to view the data to each single limit state or to the different ADOPT-Modules. This would imply that these units are on the same hierarchical level and that the MMI offers three different levels of detail.

Additionally, as the DSS also shall support the hypothetical reasoning or “what-if”-questions, an editing mode will be required to enable the user to calculate the risk under different conditions. In the editing mode he could insert different values than the actual ones for a variety of parameters, e.g. speed, course, wave length and height and see how this influences the overall risk. As this would comprise data from all categories links between the editing screen and the four different units would need to be established.

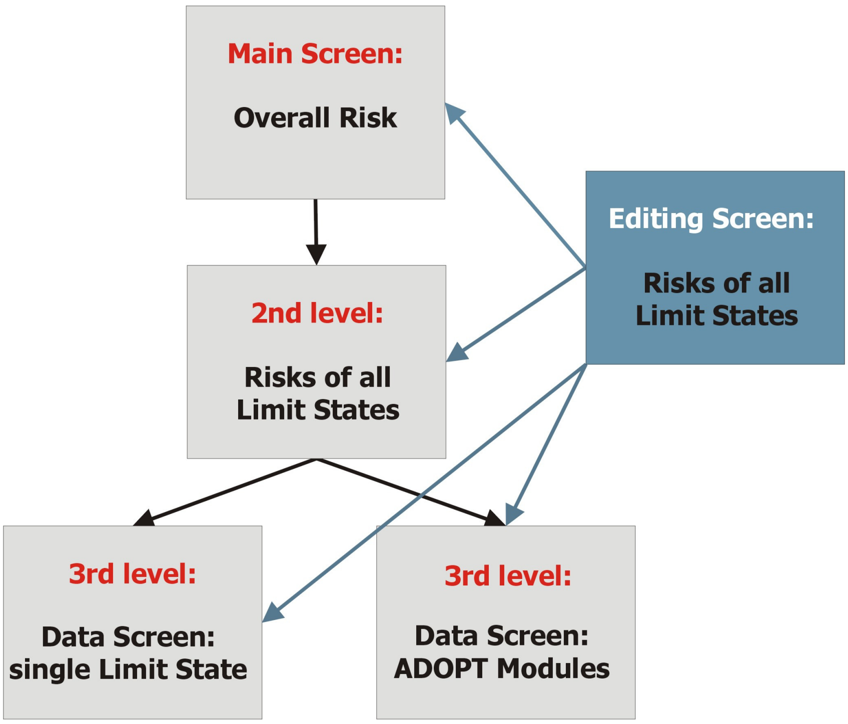


Figure 7-1: Overview of the MMI structure

7.2.2. Data Presentation

When developing the data presentation special attention was given to consistency. In a system which is used by a heterogeneous user group it is very important, that each user can obtain the required information in an easy way. Consistency also means the provision of possibilities for customization (Nielsen 1993). In this context it is the possibility to turn on/off further information or to switch to different presentations, e.g. graphics instead of simple display of data. This is achieved by using a menu bar, which allows satisfying the customization and navigation requirements.

As can be seen in figure 7-2 the main components of the risk display are the overall risk bar and the risk overview. These elements are accompanied by the display of the course and speed, as these are the main risk control options. We suggest this basic presentation as these are the main information to be given by the system on board. Primarily the user only wants to know his risk level and what he can do to improve it and nothing else. The advantage is that nothing distracts him from his task and that the representations could be given in a size which allows recognition even from bigger distances. This would enable the user to keep his mobility on the bride and would not force him to stick to the instrument. But on request the system is also able to offer further information on the right side of the screen, which can be controlled by the menu bar and therefore offer various the customization possibilities.

Figure 7-2: Presentations of the overall risk

The overall risk bar displays the risk level which is deciphered in ADOPT between negligible risk, ALARP (As Low As Reasonably Practical Possible) and intolerable risk. We chose a green, yellow and red colour index which is immediately understood by everyone. The bar representation has the advantage of additionally displaying the level of risk in the specific risk area. The user then not only knows that he is e.g. in the ALARP area, but also if he is rather near the intolerable or the negligible field. By continuous observation of the development of the risk he can with this representation also follow how the risk develops over time.

The risk overview is displayed in a polar plot indicating the ship speed on the radial axis and the course on the circumferential direction. The risk is indicated by colouring, displaying the risk level for each combination of speed and course. By that the user gets an overview what changes he would need to apply to decrease the risk of his situation and hence will be supported to come to a decision.

When displaying the risk situation in a polar plot it will have to be considered that circular representations are in a navigational environment usually used to display geographical information. Examples are the Radar and ECDIS displays, on which ship masters have been trained extensively to capture situations intuitively. Choosing circular representations therefore includes the risk of misinterpretations. As this has to be taken into account when developing the MMI Table 7-1 compares the different applications in terms of displayed data and modes of use.

Table 7-1: Comparison of Risk Polar Plot, Radar, ECDIS and 3D wave spectrum

Parameter	*Risk Polar Plot*	*Radar*	*ECDIS*	*2D wave spectrum*
Displayed Data	Speed Encounter Angle Risk level	Position (Lat/Lon) Heading Objects	Position (Lat/Lon) Map Objects	Frequency Direction Wave Energy Density
Modes of Use	Course Up North Up	North Up TM North Up RM North Up RM Course Up RM Head Up RM	True Motion (North UP TM) North Up RM Course Up RM Head Up RM	North Up Course Up

Further information that could be given to the users has been detected by conducting user interviews and relate to the environment and the specific vessel. Of particular interest to the users is the state of the sea and which wave systems exist. From the information gathered by the WAMOS system it will be possible to display the significant wave height, the peak period of waves and the mean direction of waves for the two main wave systems. These can be displayed as integers but a graphical representation indicating the direction and the frequency of the different systems would also be useful as this would make it easier to locate the different wave systems. As the wind also has strong effects on the performance of a ship its speed and direction should also be made available. Vessel related parameters would be the encounter period with waves, the own rolling period and the critical encounter period at which at the given motion of the ship parametric rolling could occur.

All these data could be made available to the user in the overall risk display level of the system. If he would like to get a more detailed insight how the different limit states contribute to the overall risk he could switch to the second level which gives an overview on that (Fig. 7-3).

The third level of the system gives then a detailed insight into the data level of the ADOPT-system. This could either be on a basis of a single limit state, displaying all relevant data to that limit state. Or it could be on a basis of the different ADOPT-Modules allowing the user to be presented all data relevant to that module. This level has not been implemented in the context of the ADOPT demonstration, but a detailed description of the available data is given in the blueprint definition of the project *(Tellkamp et al., 2007)*.

Figure 7-3: Presentation of the risk in all limit states

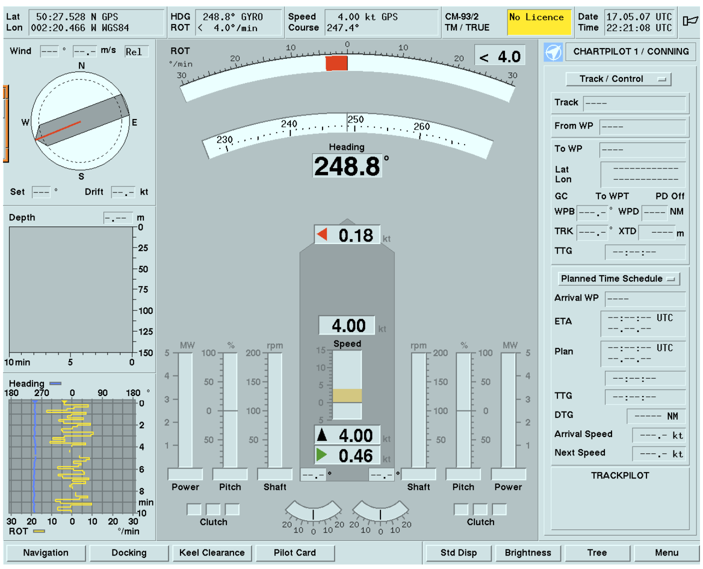
7.3. Integration of ADOPT MMI into Navigation System

7.3.1. Bridge Overview

The ADOPT user interface shall be accessible by the Officer Of Watch during critical open sea passages with abnormal sea-states. Considering ergonomic and technical constraints the best solution is the integration into the existing navigation bridge in the centre position of the main navigation console. As shown in the figure 7-4, a typical bridge layout for a Ro-Ro or container vessel comprises two operator working places, each with a Multipilot workstation combining the radar with an ECDIS overlay. Further on a chart planning system and access to automation is available at the outer positions. A Conningpilot in the centre is available for both operators. The conning screen combines the most frequently used indicators for manoeuvring and sailing as there are heading, rate of turn, position, speed, depth, wind, engine power, rudder setting and other indicators.

Figure 7-4: Bridge Layout for Ro-Ro Vessel

7.3.2. Conning Pilot



A typical conning page is shown in the subsequent picture. The screen is divided into headline, bottom line, centre area, right hand menu, and left hand instruments. This basic arrangement will be used for diagrams like history, trend, forecast (centre area). The headline will always show the actual navigation data. The bottom line allows switching between applications, one of these switches leads to the ADOPT DSS. The right hand menu is used for data access and visualisation. The presentation can be switched between daylight and nightlight colours in five steps. The screenshot shows the daylight presentation

Figure 7-5 Conning Layout, daylight

7.3.3. Chart Pilot

A typical Chartpilot page is shown in figure 7-6. The screen is divided again into headline, bottom line, centre chart area, and right hand menu. This basic arrangement will be used to visualise the vessel with restricted areas of navigation like resonance areas. The headline will always show the actual navigation data. The bottom line allows switching between applications. The right hand menu is used for data access and visualisation.

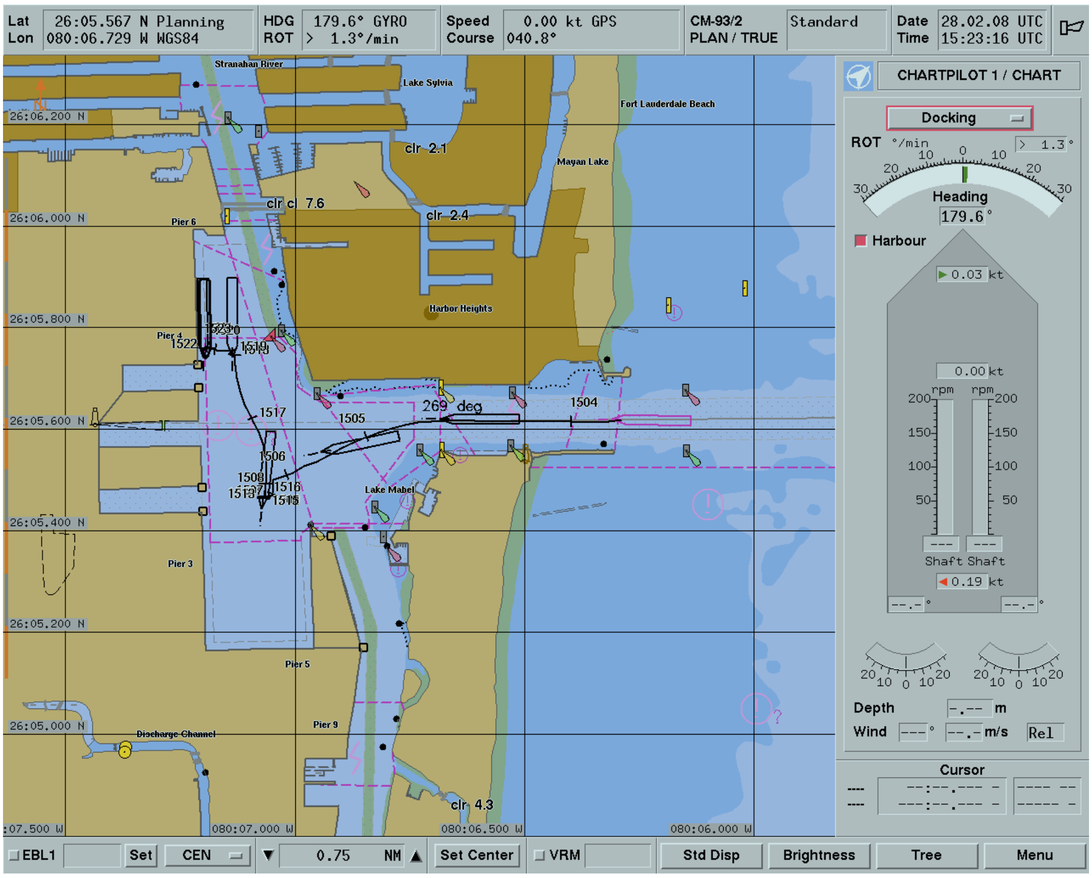


Figure 7-6: Chart System (ECDIS)

7.4. ADOPT User Interface Design Rules

Based on the NACOS style-guide, which has been developed by taking into account main IEC and class rules for bridge design, the initial ADOPT design has been created as follows:

(1) Compatibility – all the navigational information is directly shown on the user surface, nothing is hidden in a sub-menu ensuring minimum re-coding for the user

(2) Consistency – only a very reduced set of dialogues is used in the user interface

(3) Structure – in order to assist the user in developing a conceptual representation of the structure of the system, the structured area and the grouped dialogue have been used,

(4) Feedback – user feedback is given with active buttons as well as switched background colours

(5) Menu control and Display of Information – is implemented as recommended in the style-guide by a smaller right part of the application area. It is divided into a top line with

navigation data and track-pilot info, into a display scope for zoom, alarms, docking, depth, etc., into a target track data field, into a general data and menu area and into a bottom control area.

7.5. ADOPT User Interface Implementation

The main ADOPT menu shows the status of the limit states. For each limit state a single bar is presented. In Figure 7-7 the bars are divided into three sections, a green one indicating safe level, a yellow one indicating uncertain level and a red one indicating warning level. The sum of limit states is shown in the right hand section of the screen. This bar is already available in conjunction with any conning menu. The set of bars in the centre shows up on user demand only.

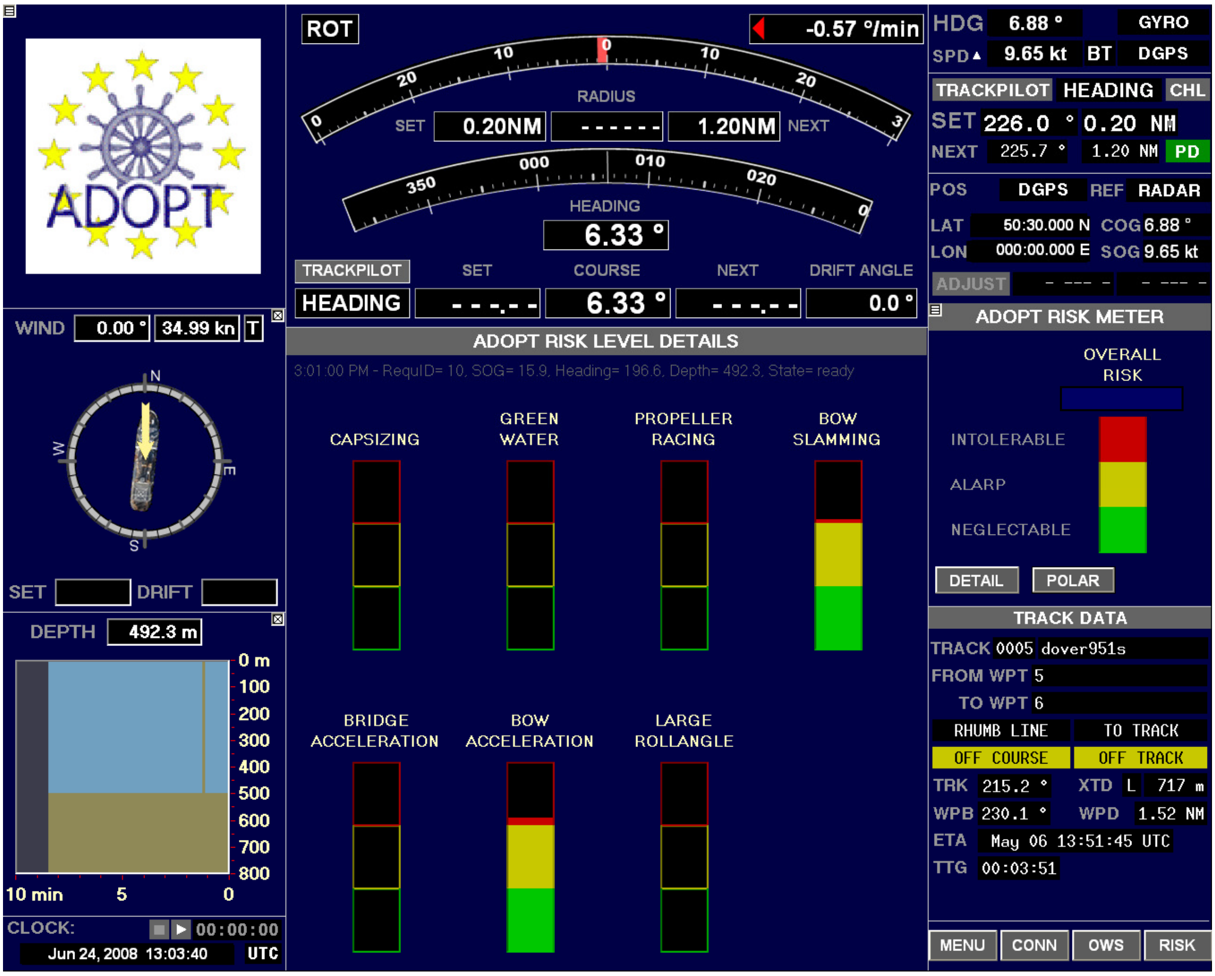


Figure 7-7: ADOPT Limit State Presentation

The centre part can be switched over to a presentation of the actual wave situation as well. Figure 7-8 indicates wave height, wave period and direction for the actual sailing condition. The values are converted into symbolic bars in relation to the vessels hull size and sailing direction. The distance between two bars gives the period, the thickness of a bar indicates the wave height.

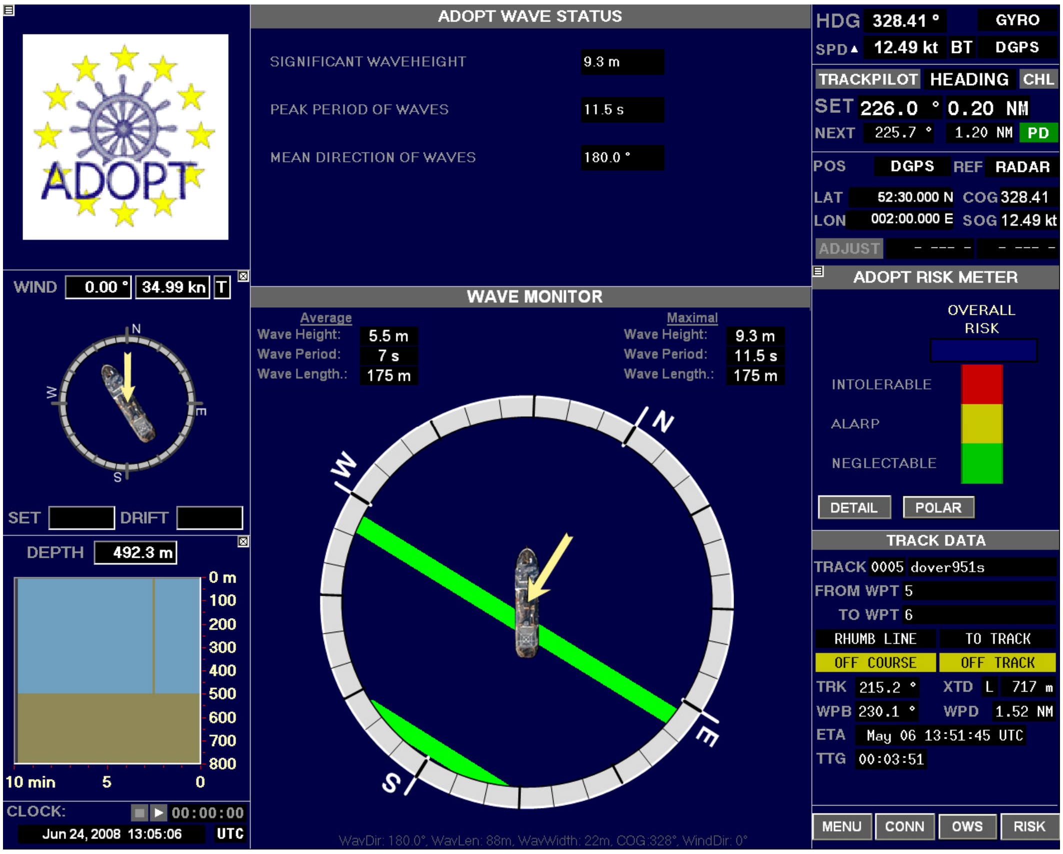


Figure 7-8: Wave Indicator

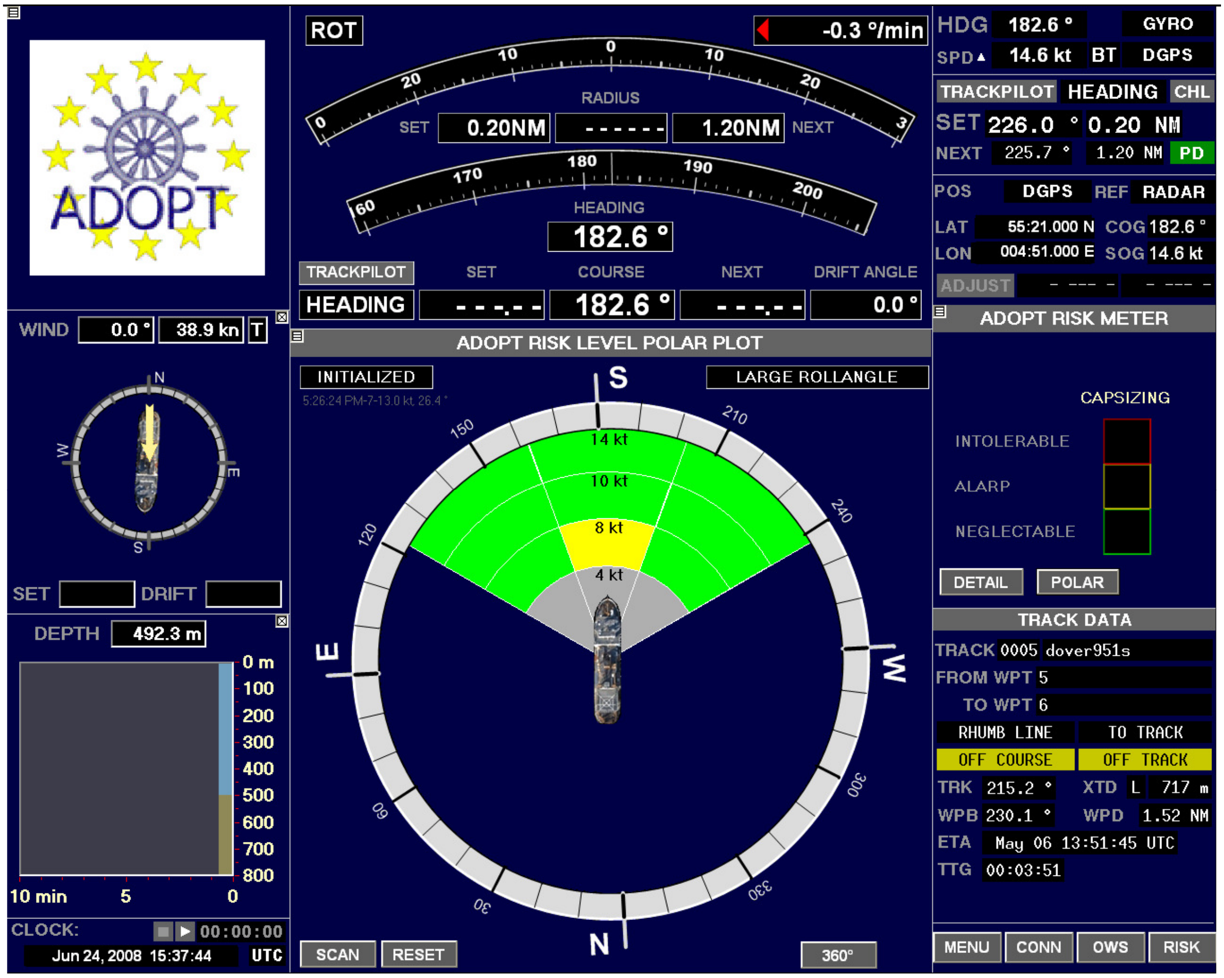


Figure 7-9: ADOPT Polar Plot

- **Presentation of selected risk for certain course/ speed combinations**
- **What-If scenarios will help to avoid i.e. parametric rolling**

7.6. Conclusions and needs for further development

We have reached an early prototype design by merging various different SW modules and tools. Integration into an existing bridge design has taken place because we wanted to evaluate the basic principles of operation as close as possible to a later implementation.

The navigators who tested the ADOPT DSS in the simulator based set-up were very impressed by the DSS and all of them stated that the DSS represented a great safety improvement compared to common practice onboard the commercial fleet today.
The features which were valued most by the navigators included:

- Estimation and presentation of actual sea state (“it is impossible for a navigator on the bridge to judge whether the significant wave height is 4 or 6 m or whether the dominant wave period is 10 or 12 seconds”)
- Possibility for assessing a number of limit states related to sea keeping – especially the limit states, which can not be “sensed” directly by the navigators like e.g. risk of

parametric roll (as opposed to the limit states which easier can be assessed like slamming and green water)
- The decision support provided by the DSS constitutes a rational basis, which makes it easier for a captain to argue for route deviations
- The DSS provides ship-owners with a risk management tool – with the ability to let the ship owner to operate all ships in a fleet at an accepted risk level
- Polar diagrams presenting consequences of heading and/or speed changes in an easily comprehendible way

In addition to this, the navigators provided a number of minor comments / suggestions for improvements. These comments and recommendations have been listed in ADOPT deliverable D7.3.

Considering further development SAM has great interest to integrate wave and risk data display into advanced navigation bridge, SAM has already the SeaSense product developed by FORCE Technology and DTU. SAM would provide a standardized data interface for ADOPT DSS kernel system, the ADOPT kernel system could be strapped down and improved in calculation speed for final application on-board.

8. Training

8.1. Introduction

As the ADOPT-DSS consists of three main parts, training as one of them plays an important role in the overall system. The general approach of Training in ADOPT is that its purpose is not only the familiarisation with the system itself but also to give advise on the background of phenomena like parametric rolling and alike, as the purpose of the DSS only can be captured when the theoretical foundation is available. By this approach the training does not only customise the user on the system but also contributes to an improved situational awareness of the risks in specific sea states.

The Training concept consists of four modules, starting with the theory. Since the ADOPT-DSS is ship specific, the theory will afterwards be consolidated by exercises in the simulator demonstrating the vulnerability of the specific ship in particular seas. Only then the issue how the DSS responds to the risks will be demonstrated. This again starts with the theoretical description how the DSS works, which are its modules and in which situations it can help. Afterwards, in the final module, the user will be customised in a simulator environment to get experience in using the system and improve his behaviour in critical situations.

Training in ADOPT is considered as one major element of the overall system. Only in the combination of all three modes, that is design, training and operation, the system will achieve its overall goal of "Assisting the master to identify and avoid potentially dangerous situations" *(Tellkamp et al., 2008)*. As the three modes are building upon each other, training depends very much on the results of the design phase. On the other hand the full benefit of the implementation of the DSS in the operational mode can only be achieved if the users are well trained in the use of the system. This highlights the importance of training for ADOPT.

It is in the nature of research projects like ADOPT that their task is to develop new technologies and demonstrate their applicability for their defined function. The exploitation of the results and their further development to make the system ready for the market is not in the scope of such projects. In terms of training this means that it can not be the goal to develop a complete training course with all its training material. The final system still can change considerably and thus availability of this material would not be an advantage for the successors who would like to make use of the results. Additionally much of the work in designing a course is spent on the development of the training material. The content and the design of the material depend very much on the participants of the course and their entry standards. But this information is only available once a training institute or any other provider decides to offer a course on the market and knows which user group it wants to target. Therefore the development of course material has not been particularly considered in this project.

We rather decided to concentrate the work on training in ADOPT on the development of a course outline which identifies the main learning objectives and presents a detailed syllabus. This approach is comparable to what the IMO has done with its model course program. Its purpose is to assist maritime training institutes and their teaching staff in organizing and introducing new training courses without presenting them rigid "teaching packages" which they are expected to "follow blindly"*(IMO, 1999)*. This approach takes into consideration that cultural backgrounds of trainees in maritime subjects vary considerably from country to country. If one only mentions the learning objectives and the required performances this leaves the instructor sufficient freedom to take the specific characteristics of his trainees into account. Additionally this generic approach gives the instructor the flexibility to develop a course which is tailored to his abilities in order to give a vivid class which attracts the interest of the participants. This facilitates the transfer of knowledge which is the main objective of training courses.

It is obvious that one aim of the training in the context of ADOPT is to practice the use of the DSS itself. That means that familiarization with the system to enable the user to fully exploit the potential of the DSS is one of the main drivers for the development of a course outline. But as well as for the project it is also one aim of the training to assist the master to identify and avoid potentially dangerous situations. This includes that the training not only needs to be restricted to the familiarization aspect. Communication with masters of vessels has shown that their knowledge about how the motion of ships is influenced by the sea rests. They have had lessons on hydrodynamics during their education, but this kind of theoretical knowledge, which is not used in their daily work, is very difficult to be applied when it was not used for a long time. On the other hand the knowledge on what determines the movement of ships has been particularly increased in the last years, leading to the formulation of the phenomenon of parametric roll.

But so far this knowledge is not transferred sufficiently to the users on board. As long as the master possesses many years of experience on board of ships this is not a big issue and can be compensated by his experience. But today the whole industry suffers a lack of qualified masters and officers making it possible to become much faster the captain of a vessel than twenty years ago. In this case the lacking knowledge on ship motions can be a problem and therefore needs to be tackled by training. With this approach the course outline of ADOPT could even be interesting for crews of ships without DSS, especially when it provides knowledge on the behaviour of specific ships.

8.2. Training Course outline and Teaching Syllabus

The following three learning objectives have been detected for a training course:

1. Introduction to the theory of ship motions
2. Awareness of characteristics and behaviour of a specific ship
3. Familiarization with a Mode 1 Decision Support System

These learning objectives can be broken down into the following required performances:
We are developing a training course which consists of four modules. The first two of them could be combined to a course "Familiarization with the ship" and comprise of a theoretical module and a practical exercise module in the simulator. It covers the theory of ship motions and the ship specific learning objectives. The other two modules can be combined to a "Familiarization with a mode 1 DSS" and likewise comprise of a theoretical and a simulator module and cover the learning objective of the same name.
The required performances which should be achieved in each of the four modules are listed below:

8.2.1. Theory of ship motions

Required performance:
Wave Theory

1. wave characteristics (regular waves)
2. superposition of waves
3. irregular waves

4. wave spectrum
5. directional spreading
6. Beaufort scale
7. ocean waves statistics
8. scatter diagrams

Required performance:
Hydrostatics

1. description of the GM
2. calculation of the righting lever curves (wave trough and crest)
3. correlation between the GM and the righting levers
4. corrections for free surfaces
5. the influence of free surfaces on the righting levers
6. corrections on the moments of inertia due to free surfaces
7. determination of the centre of gravity and imponderableness within
8. fundamentals and restrictions of stabilizers

Required performance:
Critical Situations and potential hazards

1. large amplitude roll motion (capsize).
2. loss of lashed cargo.
3. loss of not secured cargo (cars/trucks, container).
4. shift of cargo / lashed RoRo cargo.
5. shift of cargo / not secured RoRo cargo (shift within cargo unit).
6. large acceleration / injuries.
7. large acceleration / reduced crew performance.
8. green water (relative motion, damage to equipment/outfitting on deck).
9. loss of course control.
10. loss of propulsion.
11. propeller racing (relative motion).
12. wave bending moment.

8.2.2. Characteristics and behaviour of specific ship

Required performance:
Illustrate the characteristics and the behaviour of a specific ship

1. explain the design concept of the ship
2. performance of the ship in different sea states
3. particularities of the ship behaviour in different sea states
4. actions to be taken to increase the safety of the vessel

8.2.3. Familiarization with ADOPT DSS (Mode 1)

Required performance:
Describe the theory of a mode 1 DSS

1. describe the philosophy of the system
2. explain the risk based approach
3. which hazards are covered by the DSS
4. what limit states have been formulated
5. what are the limitations of the system
6. how reliable is the system

7. explain the concept of the MMI

Required performance:
Train the operation of a mode 1 DSS

1. operate the system to get to know the buttons
2. approval of correct interpretation of the situation
3. approval of being able to use the system to improve the risk situation

8.3. Conclusions and needs for further development

The validation of the training concepts has been performed through:

1) Objective measurements of skills gained during the training

2) Subjective feedback from the trainees on e.g. training concept, course structure, training objectives, scope etc.

One general comment should be given when assessing heavy weather decision support systems in simulated environments: due to the limited realism of the sensory feedback to the navigator in a simulator (the sense of the ship motions and environment is typically limited to the visualized “out of the window” view). This means that most of the limit states might be sensed by the navigator on a real ship (as accelerations and motions) while this is normally not the case in simulators as this would require installation of a motion platform. This limitation should be kept in mind when validating heavy weather decision support systems in simulated environments.

Reviews of the ADOPT training concepts made by experienced navigators indicate that the direct transfer of experiences from the design phase (typically supported and illustrated with videos from model tests or animated in a simulator) to the training phase, as it is imbedded in the ADOPT 3-mode concept, is found very valuable as this will assist the navigators in achieving a deeper knowledge of the sea keeping characteristics - and operational limitations - of the actual ship.

9. Overall conclusions and outlook

The main purpose of the ADOPT-project is to develop an advanced set of tools, based on available state-of-the art technologies, in order to assist the master on board in identifying and avoiding dangerous situations. This decision support system (DSS) provides two key features which mark a clear technical progress compared to existing systems. Firstly, the approach in ADOPT is risk-based and, secondly, the ADOPT-DSS provides true real-time decision support. Further innovative aspects of the ADOPT-DSS are the possibility of evaluating the quality and reliability of the displayed information and the use of state-of-the-art numerical methods. The reliable calculation of ship motions relies on an innovative sensing of the environment by wave radar.
The ADOPT-DSS targets a set of hazards threatening the ship's safety in heavy weather conditions, such as large accelerations, large amplitude roll motions and bow flare slamming. These hazards are formulated in 12 limit states with underlying limit state functions, defining the threshold between acceptable and not acceptable conditions.

The application of complex numerical methods in a risk based framework and the high reliability requirements made for the on-board decision support revealed the following major constraints during the development of the system:

- Within a 3 hours watch it is not feasible to obtain final results from the numerical calculations, if all uncertainties are taken into account.
- The quality of the input data is not always as high as required for a reliable decision support.
- The expertise to make full use of a decision support as complex as the ADOPT-DSS is normally not available on board.

For handling the mentioned constraints, the concept of the ADOPT-DSS was extended from a pure software-hardware package for the on-board use to a procedural process consisting of three modes of use, which are the design mode (Mode 3), the training mode (Mode 2) and the operational mode (on-board use, Mode 1), each accompanied by an appropriate set of tools. By combining the possibilities of each mode of use, the limitations shown above can be diminished and overcome to a certain degree. The time consuming calculations are done in the design mode, where the time constraint of a watch length is not relevant. Insufficient quality of input data, such as the loading condition, is solved by a quality control which uses pre-calculated data, verified in the design mode to be of sufficient accuracy.
The knowledge about the ship specific behaviour with respect to the individual hazards gathered during the design process is transferred to the crew on board via training sessions in Mode 2. Within this framework the master and the crew are also trained and familiarized with the concepts and the handling of the ADOPT-DSS. For this purpose the Mode 1 tools can be used in a simulated environment. This is an important prerequisite for the appropriate and responsible use of the ADOPT-DSS in operating conditions.

A further conclusion of the ADOPT-project is the necessity of a clear distinction between economic and safety risk as both modes are associated with fundamentally different risk acceptance criteria.

Further, two parallel branches of ship motion calculation and probability assessment have been developed, where a frequency domain provides fast and efficient decision support with respect to all limit states which show a mainly linear response behavior, whilst a time domain implementation is provided for strongly non-linear responses such as parametric rolling.

In order to meet the conceptual minimum requirements of the ADOPT-DSS, an implementation has to meet a minimum standard defined by the following specification:

- The wave sensors are able to identify multi-peak seaways, e.g. windsea and swell.
- The numerical ship motion calculations are made by state-of-the-art tools onboard.
- The Man-Machine-Interface is embedded in typical bridge equipment.
- The DSS for onboard use is preceded by the a calibration and model set-up in the design mode and training of the crew to ensure that:
  - The numerical model of the vessel is ship specific and calibrated.
  - The hazards, related limit states and the threshold values are ship specific.
  - The expertise for a responsibly and useful application of the DSS onboard by the crew is available.

The feasibility of the ADOPT concept has been proven by a demonstration prototype which was tested in a simulated environment.
At this, the numerical methods and the Man-Machine-Interface have been connected, while the sensing equipment has been simulated comparable to an on-board situation. The navigators who tested the ADOPT-DSS demonstrator in a simulator based set-up were very impressed by the DSS. All of them stated that the ADOPT-DSS represent a great safety improvement compared to common practice on-board the commercial fleet today.

From this, the consortium concludes that **the ADOPT concept has clearly demonstrated its feasibility.**

However, the ADOPT-DSS demonstrator has to be improved and further developed, especially with respect to response time, before practical on-board use is possible. Amongst others, the numerical processes of the ADOPT-DSS demonstrator have not been optimized so far. Additionally it is anticipated that the constantly increasing available computer power will assist in solving this problem in a few years.

The inclusion of relevant uncertainties from all sources (high level requirement 5) cannot be fulfilled due to time constraints. A sensitivity and uncertainty analysis to identify relevant and unimportant uncertainties may reduce the number of relevant uncertainties and thereby increase response time and/or reliability.

In the case of safety related hazards such as capsize the high level requirements regarding the display of reliability of the decision support (high level requirement 6 and 29) is only satisfied in the way of non-display, when the input data is unreliable. Improvements of the quality control and adequate displayed of the decision support reliability may be subject to further research.

Further some identified, generic hazards, such as broaching to, cannot be assessed by the numerical ship motion tools applied in the ADOPT-DSS today. Development progress on the applied numerical methods may in the future extend the possibility to include all generic hazards. The modular layout of the ADOPT-DSS also gives opportunity to include additional numerical assessment of limit states parallel to the two branches of ship motion simulation.

10. Dissemination and use

The project created a system (toolbox) that assists the captain in deciding on the navigation. The availability of such a decision support system increases the safety and cost-effectiveness of shipping operations.

The involved universities, consultants and yard use the generated knowledge in their operations and future R&D activities.

Core element of dissemination of the knowledge is the involvement of Flag State Authorities by means of an Advisory Panel. The German Flag State was involved by participation in the HAZID workshop. The project end results have been presented and discussed with the Advisory Board, involving German Flag State, the Danish Maritime Authority and Det Norske Veritas.

Overview of papers published and/or presented

D. Spanos, A. Papanikolaou, *Numerical Simulation of a Fishing Vessel in Parametric Roll in Head Seas*, 8th International Workshop on Stability and Operational Safety of Ships, Istanbul, Turkey, October 6-7, 2005

S. Krueger, F. Kluwe, *Dynamic Stability Criteria Based on the Simulation of Full Scale Accidents*, PRADS 2007

D. Spanos, A. Papanikolaou, *Numerical Simulation of Parametric Roll in Head Seas*, Proceedings of the 9th International Conference on Stability of Ships and Ocean Vehicles, Rio de Janeiro, September 25/29, 2006
This paper has been peer reviewed and selected for re-publication at the Journal International Shipbuilding Progress (Vol. 54, 2007).

D. Spanos, A. Papanikolaou and G. Papatzanakis, *Risk-based onboard Guidance to the Matser for Avoiding Dangerous Seaways*, 6th Osaka Colloquium on Seakeeping and Stability of Ships, Osaka University, Japan, March 26-28, 2008

7th International Conference on Computer and IT Applicatios in the Maritime Industry, COMPIT'08, Liège, 21-23 April 2008:

- J. Tellkamp e.a, ADOPT-*Advanced Decision Support System for Ship Design, Operation and Training – An Overview*;
- H. Günther, I, Tränkmann, F. Kluwe, *ADOPT DSS – Ocean Environment Modelling for Use in Decision Making Support;*
- S. Krüger, F. Kluwe, H. Vorhölter, *Decision Support for Large Amplitude Roll Motions based on Nonlinear Time-Domain Simulations*;
- D. Wittkuhn, K.C. Ehrke, J. Koch Nielsen, *ADOPT: Man-Machine Interface and* Training;
- D. Spanos, A. Papanikolaou, G. Papatzanakis, J. Tellkamp, *On Board Assessment of Seakeeping for Risk-Based Decision Support to the Master*.

Nielsen, U.D., Friis-Hansen, P. and Jensen, J.J., *A step towards risk-based decision support for ships - Evaluation of limit states using parallel system analysis*, Marine Structures [in press], 2008

Nielsen, U.D, *Calculating outcrossing rates used in decision support systems for ships*, Proc. IMECE, November 2008, Boston, MAS, USA.

Overview of exploitable results
All partners will use the results of the project in their core business activities. Further cooperation between some partners will lead to commercialization of the ADOPT DSS.

Overview of deliverables which are public

No	Deliverable title	Responsible for Deliverable	Nature	Dissemination level
1.1.1	HAZID Report	DNV	R	Pu
1.6.2	Report “Blue-print”-definition for DSS, summary of criteria, functionality and quality definitions and requirements with respect to the DSS and its basic components	FSG	R	Pu
2.1	Report on sea state model	GKSS	R	Pu
3.1.1	Review of methods for hydrodynamic response calculations	NTUA	R	Pu
4.1	Report describing data models for persistent ship data	SDIT	R	Pu
4.2	Report describing data models for non-persistent ship data (load cases) including uncertainty estimated from experience	SDIT	R	Pu
5.1	Report on the generic user interface modules and data representation	ISSUS	R	Pu
6.3	Report and guidelines for interfaces with existing equipment on the bridge	SAM	R	Pu
7.3.2	Report “ Training and Education concepts for and using the DSS”	ISSUS	R	Pu
7.4	Summary of experiences and further developments	FORCE	R	Pu

ADOPT project website: http://adopt.rtdproject.net

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13. List of ADOPT Deliverables

WP1: Definition of the Criteria of the ADOPT Decision Support System

Del. 1.1.1: HAZID Report (Pu)
Del. 1.1.2 A: Report on Risk Estimates
Del. 1.1.2 B: Stakeholders Requirements Specifications – Onboard DSS
Del. 1.1.3: Report on Identified risk control options
Del. 1.1.4: Report on decision criteria
Del. 1.2.1: Report of relevant quantities for environmental modelling
Del. 1.3.1: Report on min. requirements with respect to numerical motion sim. tools
Del. 1.4.1: Report on ship data requirements including adequate quality criteria
Del. 1.5.1: Report on user interface functionality requirements including quality control
Del. 1.6.1: Summary regarding the reassessment of criteria
Del. 1.6.2: Report: blue-print-definition for DSS (Pu)

WP 2: Environmental Data and Modelling

Del. 2.1: Report on sea state model (Pu)
Del. 2.2.1: Hind cast dataset including report on underlying mathematical model.
Del. 2.2.2: Data of Statistical Analysis.
Del. 2.3: Evaluation report regarding sensing of the environment
Del. 2.4: Report on methodology to be used in the DSS including definition of software
Del. 2.5: Software Tools acc. to the needs from WP 1 and as defined in 2.4.

WP 3: Numerical Modelling, Calculation Codes and Strategies for ship motions

Del. 3.1.1: Review of methods for hydrodynamic response calculations (Pu)
Del. 3.1.2: Report on strategies for limit state evaluation
Del. 3.1.3: Software tools for limit state evaluation
Del. 3.2.1: Review of present methods in available prototype decision support systems and their quality
Del. 3.2.2: Report on simulation strategies for real time decision support
Del. 3.2.3: Belonging software tools for the tool box

WP 4: Ship data and modelling

Del. 4.1: Report describing data models for persistent ship data (Pu)
Del. 4.2: Report describing data models for non-persistent ship data (load cases) (Pu)
Del. 4.3: Tools for the tool-box and implementation into DSS

WP 5: Development of the User-interface

Del. 5.1: Report on the generic user interface modules and data representation (Pu)
Del. 5.2: Report describing the functionality and set-up of the user interface in ship operation and training

WP 6: Implementation into DSS

Del. 6.1: Report on the connection of developed tools
Del. 6.2: Report on the customisation for design and application
Del. 6.3: Report and guidelines for interfaces with existing equipment on the bridge (Pu)
Del. 6.4: Report on customisation of DSS for training and operation

WP 7: Validation

Del. 7.1.1: DVD with recorded time series and data from test ship. Report with statistical analysis
Del. 7.1.2: Report: Evaluation of Onboard Decision Support Systems
Del. 7.2: Report: Evaluation of Design Tools
Del. 7.3.1: Report: "Evaluation of functionality in extreme operating conditions"
Del. 7.3.2: Report: Training and Education concepts for and using the DSS (Pu)
Del. 7.4: Summary of experiences and further developments (Pu)

(Pu): Public Report