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Operations Error Analysis of the Use of Electronic Chart Display and Information System (ECDIS)

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This study constitutes a basis for risk analysis of automated navigation aids on board of ships. The set of methods complementing each other and forming a complete operational tool combines both post-accident and predictive analyses. The post-accident analysis we use is the Accident Anatomy Analysis, while for predictive hazard identification we use the Action Error Analysis. Cognitive modelling, which we also carry out, allows a level of analysis detail even deeper than action error analysis and allows information transfer between different accident types. The basis for the post-accident analysis and cognitive modelling is the accident reports while the action error analysis is based on procedures and observations. Aiming at an approach applicable for any type of automation and humans interacting with it, we exemplify the method on one system and analyse groundings involving the Electronic Chart Display and Information System (ECDIS). Among many results and conclusions one general is that the focus on "operator error" is rather misleading, and we should consider "operations error" probabilities.

Keywords: ECDIS, electronic chart and display system, operations error, human error, action error, accident anatomy, causal diagrams.

1. Introduction

The general objective of this study was to develop an evidence-based approach to analysing and predicting possible problems in future use of automation on board of ships. The work can be considered as a basis for risk evaluation of automated functions on board of a ship. We apply existing methods for both post-accident and predictive analyses. However, we adjust them to the maritime sector and expand the taxonomy of failure modes, failure mechanisms and root causes. The two analyses constitute a consistent path to risk-based design improvements and their evaluations.

The retrospective approach we use is Accident Anatomy Analysis (AAA), developed at Risø National Laboratory, Denmark, in the 1970's (Bruun et al., 1979) This is a method for systematising and summarising information from accident reports to provide an understanding of accident causation. The core of the method consists in developing cause-consequence diagrams (CCDs) to represent accident scenario event sequences, and "causal trees" (simplified fault trees) to record a full range of adverse event causes.

The second method is Action Error Analysis (AEA), also developed at Risø National Laboratory in the 1970's (Taylor 1979, 2015). It studies the range of error and failure modes which can occur in the performance of a procedure. The "actions" can be those taken by a person, by the automation systems, or by the ships machinery. AEA is a predictive method with the possibilities and probabilities for error and for failure based on generic information. This approach is therefore only indirectly based on evidence, although collections of actual evidence exist for a wide range of activities (e.g., Taylor, 2015).

While aiming at an approach applicable for any type of automation and humans interacting with it, we analyse groundings involving the Electronic Chart Display and Information System (MAIB and DMAIB, 2021), which is an important navigation aid for ships and is an obligatory requirement for larger ships. In many implementations it provides an autonomous system of ship navigation, and in that it provides mechanisms for voyage planning generating electronic routes, and then allowing these routes to be followed by ships autopilot or manually by the helm operator. The fully automated facilities are typically used for long passages especially in open waters.

Transfer to manual control is generally made when there are difficulties, such as avoidance of other ships or navigating in shoal waters or when emergency circumstances are perceived. ECDIS itself cannot be used in these difficult conditions because it does not have input from radar or other means of detecting other ships or obstacles. Some ships are equipped with integrated navigations systems and have the possibility of overlays, e.g. displaying ECDIS, radar and automated identification system on the same display. Collisions alerts from the automated identification system can thereby be integrated in the ECDIS. The decision-making process will however at times be rooted in information from the radar automatic plotting aid functionalities.

ECDIS has lightened the workload for officers of the watch, allowing them to devote more time to look out and avoid collision, and to be aware of navigational conditions. It is not without problems however because of complexity and the large number of adjustments needed for proper use. For example, the equipment is not so good at communicating its own reliability, which the operator must be skilled at assessing, e.g. by cross referencing with other information. In some cases, the system is just used for recording, while paper charts are used for the primary navigation, leading to an increased workload. There have been several cases in which operational failure of ECDIS use has been a contributory or primary cause of ship grounding, and a number of shortcomings of ECDIS are known (MAIB and DMAIB, 2021). In this view, there is a need for design improvement and supporting tools to evaluate improvements and predict possible problems in future use.

It is commonly stated that most groundings and collisions are the result of "human error", and this terminology is even built into many models of marine risk. Indeed, there are some accidents which arise solely through errors by the master or ships officers, but by far the majority are the result of errors and deficiencies in procedures, less than adequate training, design deficiencies in the ECDIS systems or in the charts displayed, or as a result of technical failures. The term "human error" is therefore deprecated. We prefer the term "operations error" which covers all the causes.

In this paper, we briefly describe the step-by-step procedure for conducting the operations error analysis and provide an example of the application of the method, incl., a CCD, a causal tree, and an action error analysis, for some accidents caused by weaknesses of ECDIS navigation aids.

Among other outcomes of the carried study are identified human machine interface problems and possible solutions to avoid them. The knowledge gained and data collected constitute a part of the background to risk assessment of autonomous ship designs.

2. Acronyms

A number of acronyms are unavoidable, being widely used and so are listed here.

ECDIS	Electronic Chart Display and Information System
OOW	Officer of the watch
MAIB	Marine Accident Investigation Branch (UK)
DMAIB	Danish Maritime Accident Investigation Board
AAA	Accident Anatomy Analysis
AEA	Action Error Analysis
CCD	Cause-Consequence Diagram
VTS	Vessel Traffic Services
UKC	Under Keel Clearance
LTA	Less Than Adequate

3. Earlier work

Studies similar to the present one have been carried out by others using accident investigation reports as a source.

MAIB and DMAIB (2021) reports results of a qualitative study primarily based on semi-structured interviews with 155 ECDIS users and observation data gathered between February and July 2018 during sea voyages in European waters on 31 ships of various types. A number of challenges have been identified with regards to user interaction with ECDIS that are rooted in system design, practices and training.

In Baker and McCafferty (2005), 100 accident investigation reports from the Canadian Transportation safety board and 150 reports from the Australian Transportation Safety Bureau were analyzed. The conclusion was that 80 to 85% of accidents involved human error, with 50% being initiated by human error, and up to 35% with human error contributory to the accident.

In Tang et al. (2013), 319 accident investigation reports of all types of marine casualties were made by the MAIB, identifying 21 different cause types.

The paper by Uğurlu et al. (2015) studied 131 grounding incidents, with three classes of voyage management errors, five classes of team management errors, five classes of navigation performance errors and five classes of individual (personal) errors.

Ishak et al. (2019) made a questionnaire study of the root causes of error in marine activities, identifying fatigue, lack of technical knowledge and interpersonal communication problems as the prime root causes.

Turna and Ozturk (2020) made a study in which a total 80 investigation reports of grounding accidents from 2008 to 2018 were analyzed. In 22 cases, one or more findings related to ECDIS were identified.

The main differences between the present study and these earlier ones are that here:

- Each accident scenario is considered as a series of events and actions with possibilities for error at each stage.
- This leads to causal patterns for accidents which rarely involve just a single error or failure, and rarely result in just a single approach to risk reduction. Typically, accidents involve between three and eight causes.
- Human errors are largely regarded as the result of deficiencies in management and organisational systems and weaknesses in design, rather than the prime causes of accidents.
- A clear distinction is made between root causes, error mechanisms and error modes.

4. Accident Anatomy Analysis

The AAA (originally published in Bruun et al., 1979) is intended to systematise and summarise information from accident reports. It has been used for analysis of accidents in the use of machine tools, in oil well drilling, in railway safety, in fire on containers ships, and in aircraft crashes. It relies on availability of high-quality accident reports. Fortunately, very high-quality marine accident and incident reports are openly available in several countries.

The latest use of the AAA in the maritime sector is described in Callesen et. al. (2019) to analyse fire accidents on container ships.

The core of the method consists in the development of a cause-consequence diagram, which is a causal chain of events, states and conditions following an initiating event that can, for example, be start of 'Passage planning'. The initiating event is placed on top, and a chain of consequent events is diagrammed under each other. The events are written in the imperative form in the 'Yes-No' boxes forming a causal chain (scenario). If the event is true, the following path is outputted from the 'Yes' part of the box. If the event is false, the path continues from 'No'. In the latter case, the cause of following the no-path, is stated on the left-hand side of the 'Yes-No' box as shown in Figure 1. In this figure and in the remainder of the paper 'LTA' stands for 'Less Than Adequate'.

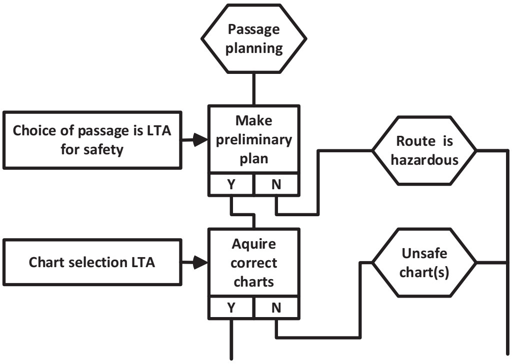


Figure 1. A fragment of evidence-based CCD for 'Passage planning'

Diagramming the chain of events, states and conditions continues all the way down to doing 'Passage' and further up to either 'Grounding' or 'Safe passage'. An example can be seen in Section 7, Figure 5.

The added value of the CCD is that several accidents can be mapped on one diagram and marked up so that each individual scenario can be traced. Marking up the scenarios gives us the immediate benefit of counting the number of the paths on the CCD providing the relative frequency of events, states and conditions contributing to accidents. The frequencies in turn constitute the necessary input to quantitative risk assessment of operations error.

5. Action Error Analysis

AEA differs from AAA, even though both produce similar diagrams. The difference is that AAA is retrospective, including only information from earlier accidents. AEA is predictive, deriving accident possibilities and causes from the full range of those which are logically and physically possible, and deriving error cause possibilities from an extensive range of observations, including process plant operation in the control room and in the field, from military, aeronautical and transport applications as well as ship navigation. It is generally possible to make much more detailed analyses with action error analysis, but the validity of the possibilities predicted need to be considered carefully; and also generally, it is necessary to derive support for the predictions from example accidents in other systems which are reasonably analogous to the one under study.

The unfoldment of the AEA consists in drawing the steps stipulated in a procedure (instruction) as a sequence of ‘Yes-No’ boxes. The ‘Yes’ outputs correspond to the correct performance of a procedure. The ‘No’ outputs from the boxes correspond to errors or to failures of the equipment. Full description of the errors and failures may require additional boxes. From the error and failure exits, the list of consequences in the potential accidents are added as event boxes.

The analysis is then completed by adding “trees” of causal mechanisms alongside the ‘Yes-No’ boxes for each error mode or equipment failure for each error or failure mode.

When identifying and predicting the causes of operations errors, we distinguish three levels in error causality: error modes, error mechanisms and root causes.

Action error modes are defined as the erroneous actions which are physically possible. For example, when following a track and approaching a waypoint, the navigation can

- omit to make the waypoint turn,
- make the turn too early or too late, or
- make an excessive turn, or fail to turn sufficiently

Such error modes reflect the physics of actions and will be the same whether the actions are made by the helmsman, OOW, an autopilot, an artificial intelligence, or whether the action error results from an equipment failure. This means that the list of action error modes can be made logically complete.

The mechanisms of failure due to equipment can be derived by failure mode and effects analysis, FMEA. The human error mechanisms, such as forgetting, erroneous steering etc. have been listed on the basis of extensive research. Descriptions of human error mechanisms for oil, gas chemical and nuclear power plants have been developed based on observations carried out over the last 50 years (see Taylor, 2015).

It is rare that errors arise in humans performing tasks such as operation or navigation without some form of external cause. If such errors can arise, they are evidence of poor design. Root causes are defined as deviations or inadequacies in management, organisation, or in design of the systems. This definition is a choice, derived from the objective of discovering ways in which risks to navigation or operation can arise. We could add inadequacies in developing regulations, or inadequacies in the form of teaching, to the list of root cause types if reducing these were an objective.

6. Operations error analysis: process, connected steps and needed data

The full-scale operations error analysis is carried out along the two branches: evidence-based (retrospective or post-accident) and predictive (logical and partially based on generic data from other industries). The outcomes of the two are then integrated to be able to conduct quantitative risk analysis and to suggest risk reduction measures. The process of performing the analysis with all connected steps and needed data is shown in Figure 2.

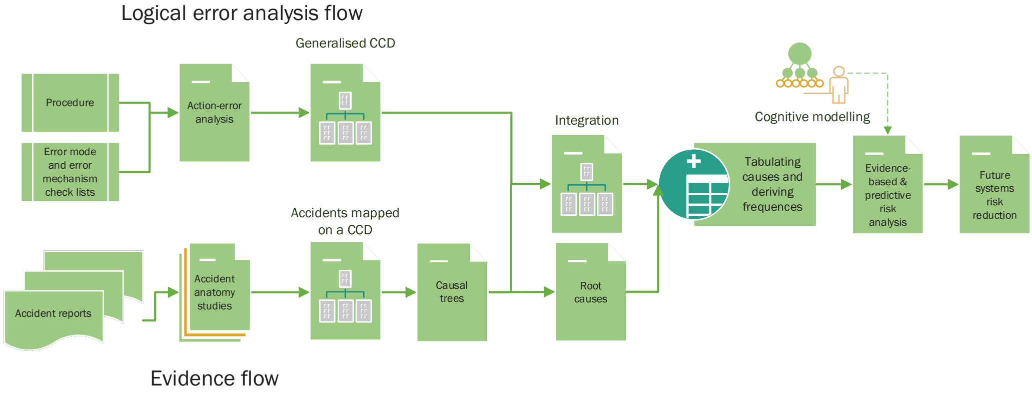


Figure 2. Operations error analysis

The analysis can also be performed in a reduced version following only one of the two branches. In this case the integration is not needed. However, being not integrated, the evidence-based analysis will suffer from being able to predict only a limited number of risks; while the validity of the predictive analysis will be questioned, as it is supported by only generic data and logically and physically feasible scenarios. Nevertheless, the either analysis will serve to reduce risks and control safety. The full-scale analysis will allow for maximally achievable improvement of safety.

The integration of the results of both retrospective and predictive analyses can be made earlier by constructing an integrated CCD based on the outcomes of the accident anatomy and action error studies. However, we would warn against doing this. The reason for the strict separation of the retrospective analysis and the predictive analysis until the late stage of the studies is that it is very easy for the analyst to impose his or her preconceptions onto the predictive analysis. This is one of the reasons for some authors giving "human error" as the major cause of accidents, and by human error meaning the OOW or the helmsman. In the studies, which we have conducted, virtually all the groundings were mediated by the OOW and/or the helmsman, as is a physical necessity, but very few of the problems were the result of inherent inadequacies of the OOW or helmsman.

The evidence-based branch of the analysis produces visualised accident scenarios and their causes on a CCD and is solely based on evidence. The causes are chosen entirely from accident reports, while for the logical error analysis flow, the list of possible causes is derived from existing generic and domain-specific checklists.

It should be noticed that accident reports are often based on judiciary normative standards and human error is by necessity a given conclusion. In this view, there is a challenge to decide which normative standard to use because the variation on how to go about using the system varies across the spectrum of its use. For example, there is not unified best practise on how to plan and execute a passage. The use of ECDIS varies form its use for recording a ships log, with the actual navigation being managed with paper charts, to another extreme in which steering is performed by an autopilot with course and waypoints provided electronically from ECDIS. The most carefully planned route plan will also have workarounds to make the system work. In the present study, the normative use of ECDIS was derived from the recommendations in the accident investigation reports which were reasonably uniform in their assessments and at least did not conflict.

Modelling of cognitive processes allows a level of analysis detail even deeper than AEA and allows information transfer between different accident types. The accident reports gave a sound basis for identifying details in cognitive models as evidenced by their correspondence with similar studies in other domains (Taylor 2015). In the study, models for situation awareness, hazard awareness and attention allocation were identified as important to ECDIS navigation and several issues for understanding and using ECDIS output were identified as well. Examples are:

- There are many different formulae for calculation under keel clearance (UKC) from different official and semi-official sources, leading to confusion or error in passage planning.
- Several UKC formulae do not include uncertainty in depth measurements given on charts into account, leading to confusion and leading directly to some accidents.
- The ECDIS HMI representation of depth contours can be misleading and require workarounds with ships officers making their own contours in order to allow safe passage alarms to work (INTERTANKO, 2020).
- Attention attracting features of ECDIS such as audible alarms either generate too many nuisance alarms or lead to muting of the alarms.

7. Operations error analysis of ECDIS

The study, which we have carried out, followed the two branches (Figure 2). To ground the evidence-based path, we analysed 27 accident reports with ECDIS related causes of groundings. All the reports are openly available from accident investigation boards. For the logical error analysis, besides the checklists for error modes (Table 1) and error mechanisms, the input is the procedures for ‘Passage planning’ and ‘Passage performance’. The main references for the procedures were the guidelines published by Khaleeque and Nadeem, 2006.

Table 1. Generic and domain specific error modes (examples)

Generic error modes	**Domain specific example**
Omission	Omission of way point
Too much/too little	Insufficient turn
Too fast/too slow	Too high speed over shoal
Too early/too late	Too early wheel over
Wrong direction	Wrong heading
Wrong object	Wrong chart selected
Wrong value	Wrong tidal depth assumed
Correct action with latent hazard	Turning with strong wind in a narrow channel
Overlook a side effect	Overlook heel (ship roll) as a result of a turn

‘Passage planning’ and ‘Passage performance’ (the latter in the following is labelled as ‘Passage’) are both initiating top events on the developed CCDs. The logical analysis produces the drawing of the CCD with a list of error modes attributed to each ‘Yes-No’ box. A small fragment of the CCD with attributed failure modes is shown in Figure 3.

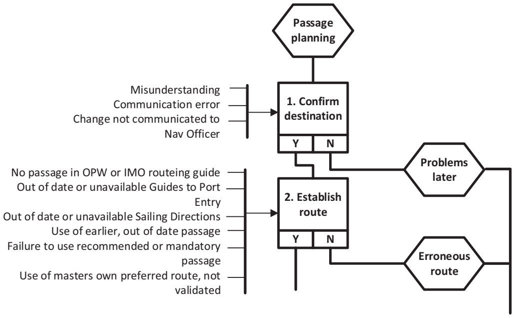


Figure 3. A fragment of the predictive CCD for 'Passage planning'

The identified causes of errors under ‘Passage planning’ and ‘Passage’ are analysed at three levels of causality. The outcome of this analysis is causal trees. An example of a causal tree is shown in Figure 4. The root causes are not shown in this figure but broadly classified into the four groups: (1) fatigue, (2) LTA knowledge, (3) LTA planning procedures, and (4) LTA ECDIS model specific training.

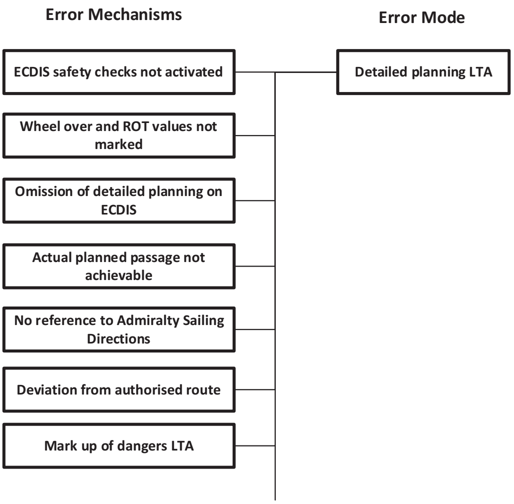


Figure 4. An example of a causal tree (fragment from 1 of 15 trees)

Passage planning is the activity preceding the actual passage performance that can result in groundings. Thus, the next and final phase of the analysis is development of a CCD for 'Passage'. From this point, the analysis is split into the three branches: grounding arising from

1. navigation over a shoal or obstacle,
2. veering from the track, and
3. missing a way point.

Cause-consequence analysis of 'Passage' is carried out for the both flows: evidence-based and logical (predictive). The same way as it was for 'Passage planning', input for evidence-based analysis is accident reports, while input for logical analysis is error analysis procedures and checklists. The CCD shown in Figure 5 with the indicated error modes is derived based on the analysis of 27 accident reports. Despite the sample is not large, rough quantitative estimates of the frequencies of a number of error modes and mechanisms are possible, as will be seen in the next section. The more accidents are analysed and following the same approach, the more reliable the estimates of the frequencies are.

The integration of the two CCDs from the different branches allows for having an overview of all identified causes of operations errors. To facilitate the extraction of quantitative information for probability estimates of operations errors resulting in groundings, it is convenient to group the errors into larger groups, as a fine fragmentation can leave many elements without attributed to them any probability estimates. Examples of the groups are shown in Table 2.

As mentioned earlier, operations error analysis can be made only for one branch of the full-scale analysis. In this case, the table summarising identified causes of the errors will be either evidence-based or logically generated. In fact, our study summarises only evidence-based identified causes. This is because we have not attempted to find the specific procedures/guidelines that were used by the ships, the accidents of which we have analysed. For this study, we have scrutinised only one procedure published by Khaleeque and Nadeem, 2006.

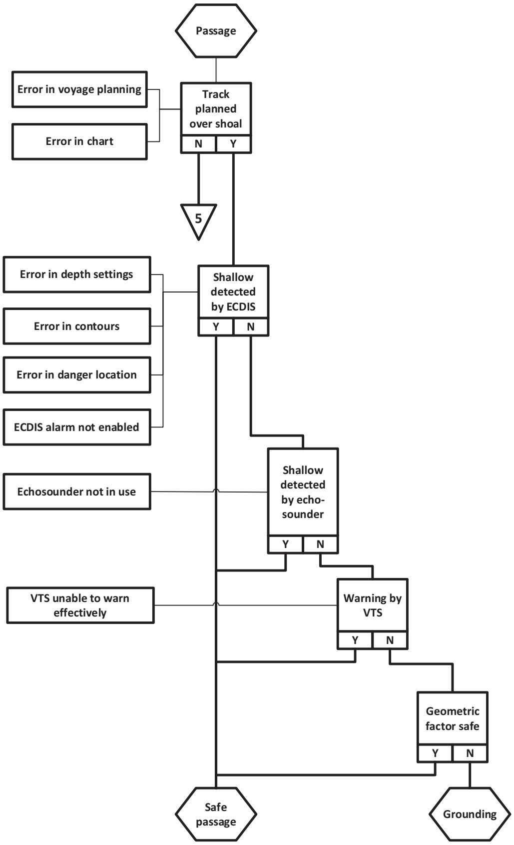


Figure 5. The cause-consequence branch for grounding arising from navigation over a shoal or obstacle

For a deeper level of detail, cognitive a modelling can be performed. However, quantitative risk assessments can be made purely on evidence if a sample of evidenced errors is representative enough to provide an acceptable level of confidence.

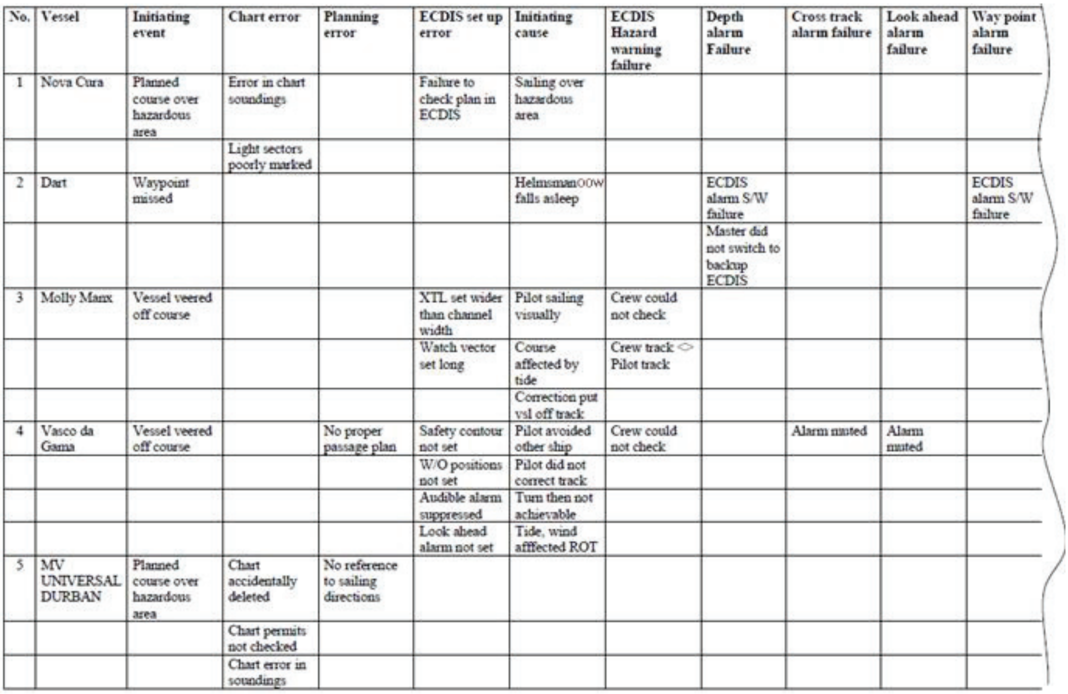
The next section explains how the probabilities of operations errors can be estimated based solely on evidence.

8. Frequencies for ECDIS related grounding causes

The frequencies of collisions and groundings per vessel manoeuvre (change of track course or collision avoidance) are known for navigation in restricted waters from many observational studies, early ones by counting passing ships, necessary manoeuvres in the observed routes, and counting of collisions and groundings. These observations can be used for calculation of probabilities, variously (mis-)termed "human error", "human failure", probability of loss of control and probability of mis-manoeuvre. This last term is used here, with the usually used symbol P_c.

Values of P_c have been given between $0.6*10^{-4}$ and $3*10^{-4}$ per manoeuvre action, with a most typical value of $2*10^{-4}$ (Gluver and Olsen, 1998). The probability of grounding is obtained by multiplying this probability together with a "geometric probability" (Rasmussen et al., 2012) which expresses the conditions in which the departure of a vessel from the desired track will lead to an actual grounding. The probability of grounding in mid ocean, for example, has a geometric probability of 0.0, and the geometric probabilities in open water will be low, while mis-manoeuvre in a narrow channel will lead to grounding with high probability.

Table 2. An extract from the tabulation of causes derived from the retrospective analysis



No.	Vessel	Initiating event	Chart error	Planning error	ECDIS set up error	Initiating cause	ECDIS Hazard warning failure	Depth alarm Failure	Cross track alarm failure	Look ahead alarm failure	Way point alarm failure
1	Nova Cura	Planned course over hazardous area	Error in chart soundings		Failure to check plan in ECDIS	Sailing over hazardous area					
			Light sectors poorly marked								
2	Dart	Waypoint missed				HelmsmanOOW falls asleep		ECDIS alarm S/W failure			ECDIS alarm S/W failure
								Master did not switch to backup ECDIS			
3	Molly Manx	Vessel veered off course			XTL set wider than channel width	Pilot sailing visually	Crew could not check				
					Watch vector set long	Course affected by tide	Crew track <> Pilot track				
						Correction put vsl off track					
4	Vasco da Gama	Vessel veered off course		No proper passage plan	Safety contour not set	Pilot avoided other ship	Crew could not check		Alarm muted	Alarm muted	
					W/O positions not set	Pilot did not correct track					
					Audible alarm suppressed	Turn then not achievable					
					Look ahead alarm not set	Tide, wind afffected ROT					
5	MV UNIVERSAL DURBAN	Planned course over hazardous area	Chart accidentally deleted	No reference to sailing directions							
			Chart permits not checked								
			Chart error in soundings								

To make an estimate of the ECDIS related error probability, we selected and screened 50 accident reports, representing all of those made available online from the DMAIB, NMAIB, ATSB and CTSB. Of the 50, 19 were grounding accidents, and of these 3, or 14% were ECDIS related. Although the sample is small, this is here interpreted as giving a probability of error of $0.14 * 2 * 10^{-4} \approx 0.3*10^{-4}$ per manoeuvre. This value is based on data from the mid 1992 through 2020. It can be expected that the probability has changed over this period, with more vessels using ECDIS as the prime or only basis for navigation, but with improving training in the use of ECDIS and improving quality of the equipment and software. However, any improvement is not yet reflected in the accident statistics.

The probabilities for the different causes of operations errors can be estimated from the counts of the cases. A part of the data as an example is provided in Table 2.This table was formed solely on the evidence-based analysis of 27 accident reports involved ECDIS related groundings. Note that some of the classes are covered by only one case, so that the uncertainty in probability estimates is large.

ECDIS has two types of roles in the accidents. One role is that of directly causing an accident or facilitating an error in planning which leads directly to an accident. Many of the errors could have occurred with similar modes in both ECDIS and non ECDIS navigational modes, e.g., an out-of-date ECDIS chart could be used because of lack of internet services for an update, or because paper charts were not available in time from a local ship chandler.

The direct causes of navigation error deriving from ECDIS were:

- Oversimplification of representation of dangers due to difficulties of conversion of paper charts to electronic format.
- Hiding of category zones of confidence information to avoid clutter on the limited space of ECDIS displays, with activation only after complex option selections.
- The frequent need to switch off depth and other alarms in inshore waters when they are most needed because of the excessive number of alarms and oversensitivity. ECDIS encourages belief in its safety, but it does not provide full safety when audible alarms are switched off or alarm lists are overloaded.
- Uncertainty about the actual meaning of under keel clearance (UKC) as interpreted by ECDIS. In all five ECDIS user manuals studied, UKC was displayed as a single number at the start of a passage with no guidance of the value in the manuals (not surprising because guidelines for this are a shipping company decision and vary widely). The variation in actual clearance with tides at specific times was accounted for directly in only one of the ECDIS systems studied. This meant that actual values entered needed to be based on worst cases, which in turn led to

excessive alarms and in some cases audible alarms being switched off.

- Several investigation boards noted the excessive reliance on GPS and the reduced taking of sightings to confirm ship position.
- In a few cases, ECDIS or its related sensors simply failed without the failure being noticed

The other role in accidents is that of failing to prevent the accident through alarms once the accident event sequence has commenced. Some of the accidents have direct causes which are not ECDIS related, such as the watchkeeping officer falling asleep, but involve ECDIS failing to recognise and alarm the incident consequences. All these accidents have multiple causes.

A general problem is that ECDIS works well in the majority of cases but at the same time encourages dependence on it, which means that when deficiencies arise, the problems may not be noticed or may be considered unimportant. It was evident from most of reports that OOWs and masters were often unaware or ECDIS weaknesses. The intense focus on navigation needed when using paper charts is reduced due to the ease of ECDIS.

Classification of the root causes could not be made sufficiently consistently from the accident reports for a complete relation to the causal mechanisms to be established. Important root causes, contributing to many accidents were lack of training with ECDIS, either in general or of specific manufacturer's models; less than adequate bridge resource management; and muting of alarms due to overload, particularly with nuisance alarms.

Table 3 shows the key events and first level causal mechanisms for an illustrative subset of the groundings, derived from the accident anatomy study. Some of the accidents require more than one cause, even for a single operations error mode. For example, ECDIS alarms will not prevent an accident if the audible alarm is muted or disabled, and if at the same time the vessel passage is not being tracked visually on ECDIS. Since such accidents did actually occur, it is clear that this pair of conditions occurred. Table 3 shows the relative frequencies for each of the first level causal conditions. As can be seen, each accident involves several causes (in the data collection, up to 8 causal mechanisms and up to 6 root causes in individual accident reports).

9. Conclusions

One of the general conclusions drawn from the analyses is that nearly all accidents involve errors that are caused by influences external to the OOW or helmsman, and the only role of the operator is to mediate these influences. The prevalence of these conditions shows that the focus on "operator error" will be misleading, and we should consider "*operations error*" probabilities (Taylor, 2022).

The described operations error analysis may appear to require too many resources to be applied for every passage. However, as soon as a repository of premade action error analyses is established (as in Taylor and Kozine, 2022) along with generalized cause-consequence diagrams and checklists of failure modes and mechanisms, the analyses then become rather an affordable routine that can also be semi-automated.

A detailed study was made of accident investigation reports for 27 cases of grounding in which failures in performance or use of ECDIS were involved. The motivation for this was the need for proper understanding of difficulties with automated navigation, prior to investigation of safety of future autonomous functions in ships. The presence of several problem types was identified, which reduce the value of ECDIS as a safety measure. (It is presumed that ECDIS does actually increase safety, but the form of this study did not allow this to be investigated.

The study identifies some clear issues which need to be investigated. As a starting point though, a systematic set of error probabilities for different types of error and failure has been established. For future studies, this set provides the basis for more detailed hazard assessment including the investigation of human machine interaction gaps and weaknesses.

In forthcoming reports, it is intended to make similar studies for other navigation equipment as a background to assessment of new and advanced navigational automation.

We can see one more added value of the performed studies. The reporting of the causes of accident investigations can benefit from the detailed three-level causes' taxonomy of operations errors, which are error/failure mode, error/failure mechanism and root causes.

Acknowledgement

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Table 3. Examples of the relative quantification of causes

Accident scenario type	**Count**	**%**
Planned course over hazardous area	12	48
Vessel veered off course	10	40
Waypoint missed	3	12

Navigation chart problems	**Count**
Danger plotted approximately from old charts	4
Chart downloading problems	3
Chart sounding errors	3
Errors in marked isolated dangers	2
Errors due to marking reefs as isolated dangers	3
Navigation light sectors poorly marked on ENC	1

Passage planning problems and errors	**Count**
Change in passage plan during passage	3
Passage did not follow a mandated route	2
Error in calculating safe depth	1
Failure to take tides into account	1
Isolated hazards not recorded in passage plan	3
No references to Sailing Directions	Many
No reference to Notification to Mariners	Many
Out of date software	2
Parallel indexing or track error limits not used	2
Passage planning made on inappropriate scale	3
Unsafe passage plan amendment	3
No senior officed check of passage plane	2
No proper passage plan made	4

Passage planning error root causes	**Count**
Inexperienced office making the plan	7
LTA training	11
LTA passage planning procedures	6
Complacency and lack of attention	4
Mismatch of master's navigation practice and authorised routes	2
Software inadequacies	14

ECDIS related error or omission type	**Count**
Error in planning over CATZOC C or worse	2
Bad safety UKC settings	2
Safe depth contour not set or misleading	6
LTA cross track limits settings	2
LTA lookahead settings	4
Safety feature options not set (unspecified)	2
Audible alarm not activated or muted	12
Bad chart scale used in navigation	3
Echo sounder available but not used or no alarm	2
Radar not set to alarm	1
Compass error	2
GPS error	1
Failure to check passage plan with ECDIS	7
ECDIS passage plan checking by software LTA	5