

Improvements in rules and regulations to support sensemaking in safety-critical maritime operations

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ABSTRACT: The ability to handle maritime operations is increasingly dependent on control systems. Such systems play a crucial role in critical situations, by presenting safety-critical information that allows operators to make sense of the situation, i.e. sensemaking. Rules and regulations influence design of the systems and training, both key areas impacting safety. This paper is based on regulations in Norway related to design, operation and training of maritime operations involving dynamic positioning (DP) and navigation systems used on the bridge. We have explored accident reports, observed work, performed literature review and interviewed actors (regulators, designers, seafarers, and certification agencies) to get a sound basis for our suggestions. We find that rules are improving slowly and that there is little focus on Human Factors (HF) design from basic ergonomics through support of cognition. Totality of rules has not been adopted to support sensemaking. Technology driven implementation may not support critical tasks and the users can be subjected to stress, poor sensemaking and conditions leading to accidents. Our suggestion is to support functional regulation, focus on HF from design, use critical "safety-cases" and verify training periodically.

Keywords: sensemaking, critical operations, safety, maritime, dynamic positioning

1. Introduction

1.1 Background and challenges

The level of maritime accidents has seen a significant reduction in the last century – however looking at the last period some discrepancies are seen. International statistics from the period 2000-2012 show that fatalities per ship year, i.e. frequency of loss of life has been reduced. However, frequencies related to the occurrence of serious accidents show increased values of about 30% (Eleftheria et al. 2016). This trend is also present in Norway, in the period 2004-2014, personal injuries have decreased considerably, but frequency of ship accidents have increased (Norwegian Maritime Authority, 2015).

This paper aims to understand how the risks of these ship accidents can be reduced. When discussing risk reduction, we base our scope on Lund and Aarø (2004), i.e. that risk reduction must be based on a broad set of actions – including regulation, technical design, training and awareness of the situation (i.e. the result of a sensemaking process).

One development in the maritime sector has been that automation, systems and alarms are increasing on the ship bridge. This is increasing the burden on human actors that must make sense of what is happening during normal and safety-

critical situations. Increased automation may reduce the workload but creates an "out of the loop" environment, removing the operator from direct control as automation takes more control. When automation fails during complex situations the operator may not understand the situation, i.e. having a situation of poor sensemaking being "out of the loop". We are interested in exploring whether the design of computer-based control systems influences the level of accidents. In order to understand and improve the handling of safety-critical situations, there is a need to address both the design of safety-critical systems and the training to enable operators to deal with the unexpected. None of these issues can be understood in isolation from human, technological or organisational context of which they are part, such as regulations and Human Factors (HF). The science of HF is an important foundation for understanding operations and critical tasks. HF consist of ergonomics (workplace layout, working postures); cognitive issues (mental workload, decision, information systems, task analysis) and organisational issues (communication, effective teams/Crew Resource Management, work processes).

The establishment of rules and regulation is a challenge due to the international characteristic of the maritime industry, and the strong focus on self-regulation and cost-optimization. Too strong

regulation in one country may drive costs and may influence shipping to move to another flag-state – thus there is a need for positive influences such as knowledge, collaboration, and benefits such as safety. Our focus on rules and regulations are based on a safety perspective, i.e.:

- The need to formulate industry good practice as rules, in order to force laggards into line;
- The need to formulate rules in order to raise the standards higher;
- The need to formulate rules when the consequences of failures are significant.

The analysis and future mitigation of an accident is based on models used to analyse accidents. The models will determine the perspective of the accident analysis and guide the conclusions, as described in "What-You-Look-For-Is-What-You-Find" in Lundberg et al. (2009). In the maritime sector the accident reports, (from Marine Accident Investigation Branch – MAIB) are often based on Reason's "Swiss Cheese" model of accident causation (Reason 1997). This model includes some technical and organisational issues – but does not include a full focus on the design phase or human factors, as in HFACS – the Human Factor Analysis and Classification System as described by Reinach and Viale (2006). This may lead to using the old concept of "human errors" as a root cause, see Allianz (2018), and not analysing the incident with a modern system perspective. In Allianz (2018) it is stated that more than 75% of marine accidents can be attributed to "human error". We use the system perspective, i.e. that "human error", is a symptom of trouble deeper inside the system (Dekker 2001, 2002). To understand failures, you must study features of people's tools, task and operating environment, as well as understand and learn from successes and recoveries. The theory of HRO - High Reliability Organisations (Rochlin, 1996; Roberts, 1989) argues that high reliability and avoidance of errors is an organisational trait, thus human error is a symptom of organisational issues. We argue that accidents and successful operations are impacted by organisational issues, and by designing and implementing systems that supports the user. Thus, we support the view that "human error" is a result and not the root cause of accidents.

1.2 Definitions and terminology

We use the term safety-critical to denote situations or operations that, if they go wrong, have a large potential for causing harm to people, property or environment. Critical operations on the bridge include voyage planning, navigation, positioning and manoeuvring the ship during the

voyage. Key systems used on the bridge are DP systems and navigation systems.

We base this discussion on sensemaking as "a process, prompted by violated expectations, that involves attending to and bracketing cues in the environment, creating intersubjective meaning through cycles of interpretation and action, and thereby enacting a more ordered environment from which further cues can be drawn" from Maitlis and Christianson (2014). The pragmatic approach is to look upon sensemaking as a dynamic process loop of observing, orienting, and acting. This process is on-going in a social setting creating and supporting understanding. It is both a retrospective and a prospective process, supporting understanding and supporting how to build and adopt resilience (i.e. ability to handle unanticipated situations) through future actions.

Safety is related to accidental harm, while security is related to intentional harm. Safety is defined as: "the degree to which accidental harm is prevented, reduced and properly reacted to" (Firesmith 2003).

The concept of resilience engineering is an important strategy to handle unanticipated incidents. Hollnagel, Woods and Leveson (2006) define resilience as "the intrinsic ability of a system to adjust its functioning prior to or following changes and disturbances, so that it can sustain operations even after a major mishap or in the presence of continuous stress". Handling of unanticipated incidents and continue to operate safe is a key ability when automation is increasing.

1.3 Key regulations

Regulation impacts design of control systems and the bridge is based on a hierarchy of regulations from the International Maritime Organization (IMO), flag state regulations, guidelines from classifications societies, industry guidelines and company specific guidelines.

The IMO conventions such as SOLAS (The International Convention For The Safety of Life At Sea – supports sensemaking. As an example chapter V-15 – Principles relating to bridge design, design and arrangement of navigational systems and equipment and bridge procedures, specifies: "the design and arrangement of navigational systems and equipment on the bridge and bridge procedures shall be taken with the aim of facilitating the tasks to be performed by the bridge team and the pilot in making full appraisal of the situation and in navigating the ship safely under all operational conditions" – however the process to reach this goal is not clearly described. There is a set of specifications related to bridge equipment such as IEC 62288 – " Maritime navigation ..." but no system view, and lack of integrated standards covering bridge systems and

navigation systems. A HF-based standard such as ISO 9241-210:2010 "Ergonomics of human-system interaction..." are not so often referenced or used. Relevant DP guideline has been updated in 2017, IMO - Circ.1580 (2017), specifying requirements for DP system redundancy and levels. Other key industrial standards are the training standards – such as IMO's International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), latest version from 2010.

1.4 Scope and Research Questions

The key challenge has been to explore maritime accidents related to electronic bridge systems and DP systems. The theme of this paper is to discuss conditions that impact sensemaking and through the sensemaking, the necessary human actions in a safety-critical situation. Three areas supporting sensemaking has been selected: design, rules/regulations and training. Based on the preceding introduction, the research questions (RQ) we want to explore are:

- RQ1: What is the relationship between design and accidents, i.e. is (poor) design a significant contribution to accidents?
- RQ2: What are the causes of accidents involving control systems used in critical operations – that can be mitigated by design or training?
- RQ3: What improvements should be suggested to rules and regulations in order to support sensemaking in safety critical maritime operations

2. Methodology and approach

We have based this paper on several sources including interviews, a review of selected accident reports, and a focused literature review described in the following.

We have performed interviews with actors in the maritime sector, to cover the activities from specification of ship/ship design through training and operations. Thus, we have included decision makers, designers, researchers, users and regulators to discuss relationship between rules/regulations, design, sensemaking, and training.

We have performed a limited literature review of the relationship between poor design and accidents. The literature review based on a keyword search of "design causes of accidents in maritime sector" using Web of Science, SCOPUS and Google Scholar (limited). In addition, we have reviewed papers focused on DP accidents through a keyword search using dynamic positioning and accidents/incidents in the search.

We have reviewed accident reports to identify root causes, especially related to loss of situational awareness (i.e. poor sensemaking process), poor design, poor training, poor ability to handle the unexpected – and if these root causes may be mitigated by improving rules and regulations. To focus our review on systems used by people we have selected accidents that involved onboard control systems, i.e. accidents which were supposedly involving onboard electronics in some shape or form. We have selected 19 accident reports in collaboration with an expert within the area of maritime safety. The review included 14 Marine Accident Investigation Branch (MAIB) investigation reports from accident occurring in the period 2005 – 2016 as well as 5 other investigation reports from accidents occurring in the period 1995 – 2008. We performed the review focusing on "loss of situational awareness/ poor sensemaking", "poor ability to handle the unexpected" and "poor design".

3. Results and discussions

In the following section, we have documented the findings from the literature review, from the analysis of accidents reports and the results from the interviews.

3.1 Findings from literature review

Searching for literature on design causes of accidents in the maritime sector, we found (Mišković et al. 2018) in addition to Rothblum (2000), Chauvin et al (2013) and Dong et al. (2017). In addition, we found a general article discussing the contribution of design to accidents, Kinnersley et al. (2007). Ibid are discussing the proportion of accidents that have their root causes in design. Based on a review of accidents in aviation and nuclear industry they conclude that approximately 50% of all accidents have root causes in design. No analysis of the maritime industry was performed, but poor equipment design was cited as a causal factor in one third of marine causalities (Wagenaar et al. 1987). In general, it is seen that poor design is a significant cause of accidents.

Mišković et al. (2018), mention that poor design was a root cause of adverse situations and prolonged the time of the seafarers to familiarize themselves with the systems, in an environment with shorter handover times. There were differences in settings and interfaces between different manufacturers. Inadequate HMI (Human Machine Interfaces) has been identified as one of the factors contributing to adverse situations. Design can negatively impact situation awareness, voyage plan monitoring, workload and stress. More automation detaches the seafarer from the control process, i.e. "out-of-the-loop" and leads to increased cognitive demands.

In Rothblum (2000), the main HF challenges were listed as fatigue, inadequate communication, inadequate general technical knowledge, inadequate knowledge of own ship systems and poor design of automation (i.e. poor design pervades almost all shipboard automation leading to accidents such as collisions). It was suggested that these challenges could be mitigated by human-centred design.

Chauvin et al. (2013) analysed 27 collisions at sea, in 1998 to 2012, using HFACS, to focus on human and organisational factors. The accident reports focused on the immediate events i.e. unsafe acts and preconditions for unsafe acts such as visibility, condition of operators, misuse of instruments – and poor reflection on framework conditions such as unsafe leadership; organisational influences; and outside factors (e.g. regulation, design). Key findings were that unsafe acts were mainly related to decision-making (85%) and from preconditions, poor visibility and misuse of instruments as the main environmental factors. In the same line, MAIB (2004) pointed out improper or poor use of radar in collision since it appeared in 73% of the cases being investigated. Related to the operators, poor situational awareness and deficit in attention appear to be major elements – i.e. poor situational awareness is often the precursor of poor decisions.

Focusing the literature search on DP systems, we found several articles. However, not many were directly related to the topics of interest for our paper (i.e. design issues, training and regulation).

The Norwegian regulator i.e. the petroleum safety authority (Kvitrud et al. 2012) explored control systems such as DP and found that there was a high level of incidents related to positioning and DP, needing to prioritise initiatives in the industry and from the regulator. The paper suggested that high attention should be given to ensure well designed and tested systems in addition to supporting a good safety culture, competence and training. Related to regulations the authorities have asked that the guidelines NORSOK N003 (2007), discussing structural design, and DNV-OS-A101 (2010), discussing requirements for design and alarms; should be reviewed and improved.

In Olubitan et al. (2018), the summarized incidents from IMCA (International Marine Contractors Association) and found that the major cause of DP incidents were the failure of thruster systems, creating the need for training of failures.

In Dong et al. (2017) the authors performed an analysis of dynamic positioning system accidents based on 9 accident reports from the period 2000-2015. The three main risk influencing factors mentioned in the reports were Shuttle Tanker positioning/control system, organisation of work (as procedures, training) and crew competence. Key root causes of the accidents/incidents related to

design/planning were: Deficiencies in DP software design; poor ergonomics/deficiency in design (poor man machine interfaces – important information was given on different monitors) deficiency in design (insufficient alarms; and massive alarms on many monitors and panels located at a large area).

There have been few papers focusing the relationship between poor design and accidents in the maritime sector, even though poor HF based design is mentioned as a contributor to accidents, such as missing information "at-a-glance" and poor alarm strategy. However, the papers point out that poor design is a significant cause of accidents.

An additional search for research literature on rules and regulations related to either design of safety critical systems or training for the use of such systems left us with no relevant publications.

3.2 Findings from interviews

We have performed interviews among regulators, designers (HF experts), suppliers and seafarers. Key issues that can be drawn from the discussions with the interviewees include:

- HF experts are seldom involved early in the design phase. Key HF principles may be missing in design; thus impacting ergonomics, cognitive issues (situational understanding) and organisational issues. Even simple ergonomics issues (such as work posture) may be poorly designed and handled.
- The principle of "user driven design" is not often used – decisions are being made between a network of actors not sufficiently involved in the actual operations of ships. Suggested ideal processes would ensure that decision makers base their request for proposal on user needs and focus on safety and resilience. Design of screens and information are seldom based on user driven design. As an example, visualisations are often based on presentation of digits and not on trend presentations; thus, information may not be grasped "at a glance".
- It takes a substantial time from problems uncovered through accident investigations are resolved in rules and regulation (i.e. 6-10 years) both internationally and nationally.
- The alarm systems are often poorly designed, and the systems may be subject to alarm flooding, i.e. the alarm philosophy is often missing. Regulation may demand that alarms are annunciate even though this may reduce the sensemaking process of the operators.
- Accident analyses are focused on "human errors" and not based on a system perspective taking into consideration poor design, missing rules and regulations. Thus, human error may be seen as a cause and not as a consequence of poor conditions such as poor design of system,

missing focus of HF and poor alarm design. HF experts are part of all marine accident investigations from day one in Sweden, but not in Norway.

- There is a need for more training of critical failures, such as loss of DP. Not all can handle the ship when DP fails. It was pointed out that training in the Norwegian sector should be validated periodically in a three-year cycle as in the UK sector, to ensure that all operators can handle critical operations.
- Checklists in the maritime sector have been improved by using best practices from aviation. The safety level in aviation is seen as impressive, there is a lot to learn from aviation in the maritime industry, as has been done by adoption of CRM. It should be an increased focus on learning best practices from aviation.

Main findings are the missing HF focus with use of appropriate standards, missing focus on human centred design and missing validation of training.

3.3 Findings from analysis of accident reports

This section describes the results from the review of 19 accident investigation reports. We wanted to focus on sensemaking, resilience, safety critical operations, training and user interfaces. Key issues in critical operations were passage planning, navigation and alarms. When discussing user interfaces (HMI) the issues were related to the use of actual electronic systems such as Electronic Chart Display and Information System (ECDIS), Electronic Chart System (ECD), DP and other systems. The results are presented, with reference to #id of accident report, the following themes sorted by number of references:

- | | |
|---|------|
| a) Loss of situation awareness/sensemaking | (10) |
| b) Poor resilience/redundancy | (9) |
| c) Alarm related issues | (9) |
| d) Insufficient training | (8) |
| e) Lacking or insufficient passage planning | (7) |
| f) Poor or missing work load assessment | (6) |
| g) Poor (safety) management | (5) |
| h) Missing or unclear regulations/standards | (5) |
| i) Poor system design or display layout | (2) |
| j) Poor bridge layout | (1) |

These categories are not mutually exclusive. Thus, some of the identified safety issues can for example describe both poor resilience and poor system design.

Loss of situational awareness due to poor monitoring of position; influence of alcohol;

distraction due to workload; unsafe navigation practices; poor passage planning; insufficient understanding of control system; misinterpretation of the nature of malfunctions. (In #2, 3, 4, 6, 8, 9, 14, 16, 17, 19). (Sensemaking not used explicit.)

Poor resilience in terms of poor organisational redundancy of coastguard; poor backup of equipment; no contingency planning; poor route planning not cross-checked; undue reliance on the ECDIS; practice of operating with watertight doors open; not using at least two independent sources to verify position; no installed navigation autopilot with alarm when discrepancies were detected. In summary, there is a need to establish resilience in critical operations such as planning and navigation. (In #9, 10, 11, 12, 14, 16, 17, 18, 19).

Alarm related issues including disabling of alarms and thus removing necessary barriers of imminent danger; alarm system silenced, missing entering of passage plan into the ECS; ECDIS not utilized effectively as navigation aid and audible alarm disabled; ECDIS safety setting not appropriate – audible alarm inoperative – defect of alarm system not being reported; system giving alarm per minute and over-whelming the watchkeeper; poor understanding of the system and relationship of alarms; navigation equipment ineffective and not set-up to use all safety features; no installation of alarm comparing position from multiple independent positions. In summary, alarm design is a key issue, and there is a need to establish best practices of alarms either through regulation or industry wide standards. (In #1, 3, 4, 9, 10, 13, 14, 15, 16, 18).

Insufficient training in terms of no emergency preparedness training; operator not qualified and not supervised; untrained in the use of the ECS and unaware of user support; no training in use of ECDIS and no safety procedures established; ECDIS training and competence should be part of the STCW code; marked differences in ECDIS systems such as menus, terminology and interfaces; poor training of electronic support systems/main engine control systems; poor training in use of the integrated navigation system; poor training in Crew Resource Management and emergency communication; poor focus on continuous professional development and skill retainment. In summary, poor training seems to be a key issue in many accidents using electronic systems (ECDIS, voyage management system, etc.). Both improved design and training is needed, appropriate to the equipment in use by regulation or industry-wide standards (such as the STCW code). The accident reports raise the issue of usability and user involvement from design through acceptance of these electronic systems – are the systems so poorly made that they are a challenge to use? (In #1, 2, 4, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19).

Lacking or insufficient passage planning including poor passage planning and poor checking and approval of the route (i.e. grounding was inevitable due to vessel draught and depth of water); poor utilization of ECS or ECDIS for passage planning – the system would have given alarms early, and plan not cross checked by the master. In summary, the quality of planning is a key issue and the support from the ECDIS are often missing (either due to poor training or poor design). (In #1, 3, 4, 6, 8, 9, 11, 12).

Poor or missing work load assessment in terms of the chief leaving the bridge due to fatigue; the sole bridge watch-keeper having to undertake passage planning and chart corrections and bridge manning was insufficient; the Coastguard being distracted and did not send warning due to chronic manpower shortages; the bridge team having to provide administrative information when they should focus on safety of vessel passage; the bridge missing an appropriately certified third person; a widespread deselection of automated functions in ECDIS to reduce workload (indicative of wider problems with the ECDIS design); In summary, organisational factors as well as design issues contribute to work load and fatigue. (In #1, 5, 8, 9, 11, 16, 18, 19).

Poor (safety) management including the Harbour not having a risk assessment or safety management plan in the pilotage area; the crew seeing no value in safety management; the master providing insufficient safety focus/culture; poor clarity in responsibility during watch; inefficient safety audits based on ISM code; poor risk assessment prior to work on ballasting; poor passage planning – not cross-checked – and mitigating actions not performed. In summary, risk-based focus of operations is sometimes missing – and there is variability. (In #1, 4, 5, 6, 7, 8, 9, 10, 11, 12, 16, 17, 18, 19).

Missing or unclear regulations/standards related to needed understanding of equipment and usage relating to electronic chart displays; need for training of ECDIS and voyage management systems not set out; absence of regulatory and industry-wide standards for training appropriate to the equipment the operators use; need for performance standards for integrated bridge systems i.e. design, installation and testing. In summary, there is a need for improved regulation and standards related to use of integrated bridge systems and ECDIS. (In #1, 7, 10, 13, 15, 16, 18).

Poor system design or display layout in terms of deficiencies in design and implementation of the integrated bridge system and in the procedures for its operation; widespread de-selection of automated functions in ECDIS that is indicative of wider problems with ECDIS; ECDIS not used as expected by the regulators or equipment manufacturer; ECDIS safeguards intended to prevent grounding were overlooked, disabled or ignored; MAIB chief

inspector said: "this is the third grounding investigated by the MAIB where watchkeepers' failure to use ECDIS properly has been identified as one of the causal factors. In 2014 there are over 30 manufacturers of ECDIS equipment, each with their own designs of user inter-face, and little evidence that a common approach is developing." In summary, there is a need for standardization, improved user-based design, and user-based acceptance testing in normal operations and during critical operations. (In #1, 4, 8, 9, 10, 13, 17, 18).

Poor bridge layout with layout of the central bridge console preventing the chief officer from utilizing the ECDIS to support the master during pilotage; In summary, bridge design must be improved and based on task analyses. (In #4, 11).

We have been interested in the relationship between poor sensemaking, resilience and poor design. We see resilience as an ability in sensemaking, to improvise and use existing systems and resources to cope with novel situations, i.e. use redundant or alternative systems (or check perception with other stakeholders) and thus reduce consequences of an unwanted situation. Looking at situations with both loss of situational awareness/poor sensemaking and poor resilience – we observe from five accident reports (#9, 14, 16, 17, 19) that poor sensemaking lead to dangerous situations and the additional poor resilience does not hinder or reduce the consequences of the situation. Thus, the dangerous situation develops into an accident.

When focusing on sensemaking, the usability qualities of the control systems (ECDIS, Bridge systems, DPS) should improve. The poor usability also influences the needed training regime, since training and competence development seems challenging (due to system complexity) and sometimes missing (due to costs, poor practice and missing regulation of training). The ability to understand the status at a glance (and get an understanding of key risks) may be missing. Passage planning seems poor due to poor usability and missing operational procedures – thus the systems do not support sensemaking as they should. The alarm systems have not been adapted to the users' workload and system understanding, thus alarms seem a disturbance and not an input to improved sensemaking.

Design of organisational procedures and work should be performed together with the seafarers to ensure usability of procedures, checklists; clarity in responsibility and proper work load. Too high work load may lead to stress and challenges sensemaking and understanding. Design of alarms should be performed to ensure that alarms are designed to support sensemaking and not stress the operators with too many alarms i.e. more than six alarms each hour as specified by EEMUA-191 (2013).

4. Discussion and conclusion

Based on our findings and the existing frame-conditions in the industry, the overall focus of regulation must be based on increased knowledge sharing and learning from accidents and mitigating actions between the regulators, the ship owners, key stakeholders (insurers and certification companies) and the workforce. The findings support the following suggestions:

- **Increased regulators' and industry focus on user centric design principles:** Poor design is a significant contributor to maritime accidents. There is a need for improved regulations and standards related to use of integrated bridge systems and ECDIS. Design of bridges and control systems should be based on user centric design principles, involvement from HF experts and should be subject of inspections, regulators and workforce attention. Benefits of user centric design should be highlighted through research.
- **Alarm philosophy must be established for all systems** – not individually for each system. The quality of alarm systems is poor and alarm guidelines and standards should be established based on industry best practices considering human limitations. Collaboration between regulators, industry and classification society should be prioritized to speed up adaptation.
- **Increased regulators' focus on training including verification:** Training in use of safety critical systems should be subject to increased regulation, and verification of knowledge should be performed periodically (each 3rd year) based on safety cases. Training should be based on safety events challenging the operator – such as loss of DP systems and speed of ability to recover/ get "in-the-loop".
- **A contemporary system perspective should be used in maritime accident analysis** – changing the perception of the old fashioned "human error" from a cause to a more systematic assessment of other root causes found to be significant contributors to accidents - such as poor design, poor training and poor procedures. Quality of accident investigations should be improved, in addition to improve information sharing and learning. Assessment of design and HF-design as a contributor to accidents should be a part of accident analyses. An HF expert should be part of all accident investigations from day one as practiced in Sweden, but currently not in Norway.
- **Continue to adopt best practices from the aviation industry.** Shipping has adopted many best practices from the aviation industry such as Crew Resource Management/ Bridge Resource Management, procedures to make checklists usable – this is a practice that should continue. As a further example – more standardization is

needed – such as in bridge systems/ECDIS equipment.

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