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Analysing seafarer competencies in a dynamic human-machine system

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ABSTRACT

Human factors have been deemed to affect a variety of unsafe acts and hazardous conditions, with no exceptions in the maritime sector. With increasing applications of automation techniques in shipping, seafarers' roles are changing, and their competencies require to be assessed and assured for safety at sea accordingly. The studies on seafarer competencies have therefore been tightly bound with a human-machine system which consists of the interaction of seafarers and ship operational systems and sub-systems. To evaluate the seafarer competencies that fit automation systems in shipping, this paper aims to develop a new dynamic human-machine model in shipping that can be used to analyse human factors in a closed-loop system. Based on Crew Resource Management and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, it reflects the input, process, and output phases of the human system and its interactions with machine sub-systems. A new tool to analyse seafarer competencies is proposed to rationalise human factor evaluation in the maritime closed-loop system and reflect the dynamic human-machine cooperation process. Two case studies have been conducted to illustrate the feasibility of the new model and in the meantime to investigate seafarer competencies in the dynamic human-machine system. It produces a new human factor analysis tool to investigate maritime accidents. The results and policy implications help explore the adjustment of maritime training to support ship automation and provide guidance on risk management for traditional and autonomous ships.

1. Introduction

95% of world trade is transported by sea, and approximately 75–96% of marine accidents are related to human factors (Hanzu-Pazara et al., 2008). There has been an overwhelming understanding that various activities of seafarers are associated with vessel conditions, environmental factors, and human and organisational factors. Meanwhile, the competence assessment of seafarers is critical in maritime training and management, as it judges the knowledge that seafarers need to obtain and the specific skills they require to learn before being deemed qualified. With the increasing automation techniques, the human-machine system, which consists of the interaction of human and machine sub-systems, is proposed for automated driving system design (Yun et al., 2019). To enhance safe shipping and improve human performance, seafarer competencies in the human-machine system have been considered in ship design and maritime accident analysis (Han et al., 2021).

Crew resource management (CRM) derives from air transport, where many injuries and deaths are caused by aviation incidents (Authorities, 1998). CRM illustrates a set of non-technical skills, including teamwork, communication, leadership, and decision-making. It has introduced applied social psychology and management experience into aviation safety regarding teamwork ability and safety performance (Mansikka et al., 2019). In addition, it has been utilised in many high-risk industries, such as surgery (Yule and Paterson-Brown, 2012), nuclear (Crichton and Flin, 2004), and shipping (Hetherington et al., 2006). In the light of maritime transport, the maritime equivalent of CRM has been applied for a long time, which is named Bridge Resource Management (BRM), or Bridge Team Management (BTM) (Hetherington et al., 2006). More risks such as psychological factors have been considered to explain safety behaviours (Fan et al., 2023). Study shows that psychological capital and burnout are more important factors than seafarers' age and experience, which explains 63% of safety behaviours (Yuen et al., 2020). In addition, the IMO recognises the significance of non-technical training and competence by describing it in the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) as "competence in crisis management and human behaviour skills for senior officers who have the responsibility of passengers in emergencies" (STCW Code Table A–V/2). However, the code revealing the seafarer competences does little to present the

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behaviour-based and result-centric competencies. Competence refers to a specific range of skills, knowledge, or ability, while competency is the quality of being qualified. As with the development of ship automation, competence may change due to new tasks and scenarios, while competency evolves with different priorities. Moreover, the development of ship automation introduces some benefits and new challenges for seafarers to obtain and maintain their competence in safe navigation. The benefits lie in the reliability of supportive sub-system of automation modules onboard. It relieves the cognitive workloads of seafarers by automatic monitoring, reducing technical manoeuvring, providing reliable information, or supportive decision-making systems. It may also ease concerns about physical health of seafarers and improve their willingness to work onboard (Wang and Shu, 2021). However, the challenges are mainly relating to ergonomic design issues, information overload, and adaptation to updated skills. Although there is decreasing crew size onboard, the interaction of the human-machine system is significant and will remain for a long time across the whole autonomous shipping era.

Previous codes and studies on seafarer competence were unable to present the interaction between competencies and machine systems given ship automation. To fulfil this gap, the paper aims to develop a new dynamic human-machine model in shipping that can analyse seafarer competencies in a closed-loop system. Two cases are analysed to demonstrate how the proposed model can be utilised for a dynamic human-machine system. The dynamic human-machine system reveals interactions between the human and machine sub-systems, which presents a closed-loop process to illustrate the input and output between components. The effective human-machine system in the maritime sector enables information transmission, duty handover, emergency management, and workload management. Furthermore, it helps identify the system's vulnerable points and evaluate the causal chain process in accidents, which serves as an effective tool to monitor and manage human performance in safety-critical systems. In addition, dynamic features of the system can be used to adjust the level of automation with human-machine interfaces in advanced ships. To evaluate the seafarer competencies given automation systems onboard, it is significant to propose the dynamic human-machine model so as to 1) reflect accident causes through accident analysis, 2) identify seafarer competencies and their association with each other or external factors, and 3) generate policy implications on maritime training aiming at increasing ship automation, providing guidance on the risk management for traditional ships and system design for autonomous ships. By doing so, this paper makes new contributions as follows.

- Development of a new tool to analyse seafarer competencies based on CRM and STCW.
- Clarification of competency elements in the maritime sector.
- Establishment of a new dynamic human-machine model to reveal the interactions between seafarer competencies in the closed-loop system.
- Rationalisation of human factor evaluation in maritime accident investigation.

The structure of the paper is organised as follows. Section 2 presents the materials and methods relating to a dynamic human-machine system in the existing literature. Section 3 develops the new evaluation mechanism of seafarer competencies in a dynamic human-machine system. In Section 4, real case studies on the new dynamic model are analysed, while theoretical and policy implications are generated based on the lesson learnt from the cases. Finally, the conclusion is presented in Section 5.

2. Materials and methods

2.1. Competency, CRM, and BRM

Competency is different from competence in the performance assessment. Competence contains a specific range of skills, knowledge, or ability, while competency is the quality of being physically and intellectually qualified (Teodorescu, 2006). The particular differences are shown in Table 1. This research focuses on investigating the required 'competency' rather than 'competence'.

In the maritime industry, there is an STCW code illustrating the seafarers' competence, but not about competency, such as STCW Code Table A-II/1 and STCW Code Table A–V/2 (STCW, 2011). However, the code with competence criteria fails to show how the standard is achieved. It addresses limited results-centric or behaviour-based knowledge required by seafarers, which reveals gaps between the rule and the practical performance. Even with appropriate training with an STCW baseline, task deviations by seafarers may lead to dangerous situations during navigation (Rajapakse and Emad, 2021). Furthermore, the competence is quite diverse, depending on the process duty and onboard operations. On the other hand, competency, reflecting the behaviour-based ability and personal attributes for human performance, has yet to be proposed for seafarers in maritime transport. Because the competency does not rely on working scenarios or specific processes, it discloses thought patterns resulting in successful performance and fits in the human-machine system.

The CRM represents the effective integration of all resources to achieve safe and efficient operation. It evolved as a training initiative for non-technical skills, developed from a series of aviation accidents with no major technical failures (Hetherington et al., 2006; Mansikka et al., 2019). CRM refers to various social and cognitive skills: cooperation and communication, leadership and managerial skills, decision-making, and situational awareness (SA) (Barnett, 2005). Non-technical skills developed from CRM training aim at training operators and reducing human errors in accidents and incidents. However, behaviour-based training like CRM is immature compared to non-technical skills and competence study in the shipping industry. Introducing the assessment of non-technical skills through CRM will help bridge gaps and attain the desired competency.

Maritime accidents revealed the same importance of human factors as that in the air transport domain, which implies that the development of CRM in the maritime industry is valid (Hetherington et al., 2006). It will provide useful insights to fulfil the gap in the existing literature on maritime competency studies. The BRM, or BTM, is the maritime equivalent of CRM. It focuses on incorporating skills, such as teamwork, communication, leadership, decision making and resource management,

Table 1
Comparison between competence and competency (Teodorescu, 2006; Sanghi, 2016).

	Competence	Competency
Definition	Worthy performance leads to the most efficient accomplishment	Knowledge, skills, mindsets, and thought patterns, resulting in the successful performance
Areas of Focus	Measurable, specific, and objective milestones to accomplish to consistently achieve or exceed the goals	Skills, knowledge, attributes, and behaviours that successful people have
	Skill-based	Behaviour-based
	Process-centric	Result-centric
	What is measured	How the standard is achieved
Desired outcome	Providing guidelines with clearly marked and measured milestones	Hiring, training, assessment, and development programs
Application	Define measurable performance standards for hiring and selection	Be given training, tools, information, and resources to bridge gaps and attain the desired competency

into organisational and regulatory management of bridge officers. In addition, it starts from a voyage with a passage plan and continues through the end of sea passage, consisting of the passage plan, keeping a navigational watch, monitoring the ship's progress, etc. (Swift, 2004). In addition, BRM courses are recommended by the International Safety Management (ISM) code and have been used by shipping companies. This study integrates the aviation pilot competency, BRM, and STCW code to develop the seafarer competency as the components in the human-machine system.

2.2. Human-machine system

Cooperative human-machine systems in maritime transport support the teamwork between humans and machines, where resources including Very High Frequency (VHF) radio, Automatic Identification System (AIS), radar, and Electronic Chart Display and Information System (ECDIS) are for effective communication and reliable navigation (Ludtke et al., 2012). Seafarer competencies and machine sub-systems form a dynamic system where feedback and interactions generate hybrid complexity. Regarding cyber-physical systems, Lim et al. (2019) propose a cognitive human-machine interfaces and interactions framework to characterise eye-tracker performances, which reveals human parameters interacting with other parameters in closed-loop systems. In the light of an automated system, the human-machine system has raised many concerns regarding human-machine interface design and operator competence requirements (Yun et al., 2019; Saha, 2021). Therefore, it is necessary to incorporate human behaviours into the dynamic system.

With the development of transport automation, human factors have been an essential component in the whole system. However, human factor analysis without machine sub-systems ignoring the interdependencies among elements will underestimate the risk evolution in severe accidents. Therefore, human-machine interface (HMI) and Human-Robot Interaction have drawn growing attention, which helps resolve issues concurrently on the human and service supplier levels of the intelligent transport system (Wang et al., 2022; Enjalbert et al., 2021). The HMI requires the system to be user-friendly, reliable, and ergonomic, while human-machine cooperation highlights the feedback and interactions between humans and machines in a dynamic way (Hoc, 2000). Complex systems involve various elements, including humans, machines, environment, and organisations. Adaptive HMIs are closed-loop systems measuring multiple parameters in conjunction with real-time command, control and display functions to support cognitive human-machine systems (Lim et al., 2019). The cooperation between humans and machines is considered in the control loop of ship collision avoidance, which supports HMIs in conflict resolution (Huang et al., 2020). The automation achieves full-automated manoeuvre without human intervention and enables the switching process between human and machine navigation modes in trucks, cars, and ships (Enjalbert et al., 2021). However, the most advanced automation of machines cannot guarantee the most selection by humans. Navarro et al. (2018) prove that the automation types offering the best human-machine interaction quality are chosen rather than the most effective automation type.

Current maritime human-machine system studies mainly focus on risk assessment methods, SA, and decision-making approaches. Among them, risk assessment methods, including the Fault Tree model (Zhang et al., 2019), Event Tree model (Ronza et al., 2003), Human Factors Analysis and Classification System (HFACS) (He et al., 2022) and Bayesian Network (Fan et al., 2020b, 2020c, 2022), are in an open-loop analysis mechanism to investigate the relationships between risk factors. It analyses different elements in a hierarchy and top-down way. Similarly, a human-natural system has been investigated for marine protected areas using a multilevel analytical approach (Ho et al., 2014). Regarding SA, a correct and reliable sense of the navigation situation is essential to safe shipping (Cordon et al., 2017). To illustrate SA, Szlapczynski and Szlapczynska (2016) utilise the ship domain to measure the degree and time to domain violation, rather than the classic method that measures distance and time at the closest point of approach. With regard to the cyber-physical system and intelligent transport system, advanced technologies and concepts have been applied to improve the existing human-machine system. For example, co-driving cars (Yang et al., 2021) and cooperative cognitive robots (Stiller et al., 2007) imply the possibility of data-driven models to generate a closed-loop human-machine cooperation system. It shows implications for dynamic human-machine system investigation. In the light of decision-making methods, Yan et al. (2019) propose a navigation brain system to make decisions through all the information of the navigation situation. A self-learning framework that designs a brain-like mechanism emphasises the evolution of a human-machine cooperation strategy (Zhang et al., 2021). However, such maritime human-machine system studies have yet to reveal risk factors or elements in a closed-loop mechanism, which requires the dynamic view to reflect the interdependencies between humans and machines in maritime transport.

Maritime transport shows similarity with aviation from many perspectives due to complex navigation scenarios and sophisticated performance requirements. The human-machine system states in a simulated air transport context can be estimated in unprecedented situations (Enjalbert and Vanderhaegen, 2017). Similarly, maritime transport can utilise human-machine cooperation into Maritime Autonomous Surface Ships (MASS) to maintain SA and improve the decision-making process of a remote operator for intelligent shipping (Liu et al., 2022). In addition, both sectors require communication and cooperation among crew members, which implies similar requirements for operator competencies. Therefore, the conceptual model of the dynamic system for flight (see Fig. 1) is used as the foundation to develop a new dynamic human-machine system that fits the urgent demand in the maritime sector for competency studies. It consists of seafarer competencies and the ship sub-system, making a complex and dynamic human-machine cooperation. The human sub-system contains seafarers' activities, and machine sub-system involves the vessel conditions and the adaptions in the ship's states. The output of human sub-system generates the machine sub-system's input. Through the internal dynamics of the machine sub-system, its output with the ship state is determined. Then the output of the machine sub-system generates the feedbacks to the human sub-system, which creates a closed-loop process. In addition, the system is disturbed by external factors (e.g., environmental factors) and the human is supposed to manipulate the machine sub-system input to ensure the difference between the machine sub-system's output and the reference signal (e.g., passage plan and regulation) is minimised.

Due to the asynchrony characteristics of such events, the differential equations of the mathematical model cannot be used to model the system (Chiachio et al., 2022). Therefore, a model describing asynchronous event-driven dynamics is required and proposed for the dynamic system. It enables the description of components, sub-systems, interactions among them, and the entire system. This study presents a dynamic human-machine system with seafarer competency components, illustrating the process of causal flows in interactions between human and machine systems.

3. A new dynamic human-machine system in shipping

The seafarer competencies have been reviewed from the STCW code, BRM, and literature. Referring to the CRM in aviation (Mansikka et al., 2019) and BRM in the maritime sector (Swift, 2004), seafarer competencies as components in a human-machine system are mainly derived from the competence of officers stated in STCW Code Table A-II/1, and crisis management for senior officers in STCW Code Table A–V/2 (STCW, 2011), as seen in Table 2. Common competencies in the aviation and maritime sector include communication, knowledge, teamwork and leadership. However, some competencies in aviation do not apply to seafarers, such as "controls the aircraft flight path through automation"

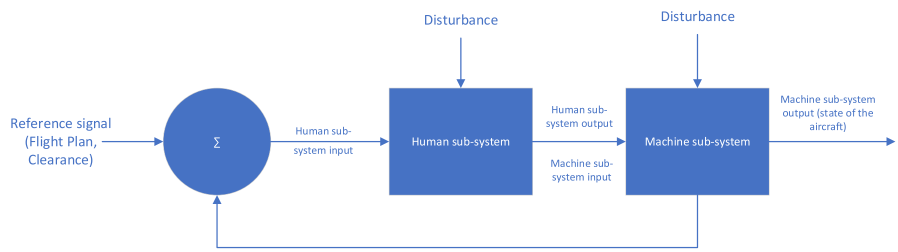

Fig. 1. Conceptual model of the dynamic system for flight deck (Mansikka et al., 2019).

Table 2
Details of seafarers' competencies.

Competency	Description	Source
KNO	Knowledge	STCW (2011)
CC	Cognitive capacity	(Fan et al., 2020a, 2021; Fan and Yang, 2023)
SA	Situational awareness	(Swift, 2004; Fan et al., 2020a)
TWL	Teamwork and leadership	Swift (2004)
PP	Passage plan	Swift (2004)
COM	Communication	STCW (2011)
DM	Decision making	STCW (2011)
EQM	Equipment correctly used	(STCW, 2011; Fan et al., 2020a)
SO	Manoeuvres	STCW (2011)
SC	Amend/maintain ship course	STCW (2011)
PO	Procedure operations	STCW (2011)
RM	Comply with regulations and management	Swift (2004)

and "controls the aircraft flight path through manual flight". Furthermore, "passage plan", "manoeuvres", and "amend/maintain ship course" are unique for maritime systems according to features in navigational tasks and highlights in STCW regulations. The difference between the two sectors (i.e., aviation and maritime) is obvious, showing the necessity and significance of this study.

The dynamic human-machine system consists of human and machine components, with the closed-loop flow comprising competency elements. Concerning some features in aviation, a new human-machine system for seafarer competencies is developed in Fig. 2. The human sub-system's input feeds to the process phase and then passes through the output phase. The output of the human sub-system links the chain to the machine sub-systems, and the output of the machine sub-system feeds back to the human sub-system's input. The disturbance influences the human process phase and machine sub-system. The differences between the reference signal and the output of the machine sub-system contribute to the task complexity to reflect on the task demand in the human sub-system input phase.

The human input phase consists of INF, KNO, CC, and TD; the process phase includes SA, TWL, COM, and DM; the human output phase is EQM, SO, SC, and PO. Of these competencies, EQM, SO, SC and PO represent technical skills required for seafarer performance, while KNO, PP, RM, SA, TWL, COM and DM are non-technical skills (Barnett, 2005).

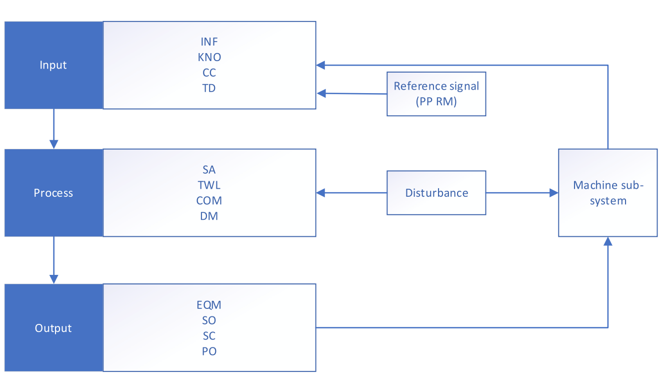

Fig. 2. Competencies as elements of a closed-loop system. INF, information; TD, Task demand.

3.1. Input phase – INF, KNO, CC, and TD

The input phase includes information, knowledge, cognitive capacity, and task demand. Among them, TD is calculated by the differences between the reference signal and the machine sub-system's output. INF represents the reliable information obtained from the nautical chart, publications, radar, ECDIS, and Automatic Radar Plotting Aid (ARPA) is relevant and accurate, so the charts are modified in accordance with the updated data and information. Also, measurements of weather conditions and meteorological data are included.

KNO includes a good understanding of relevant equipment, qualified skills, and necessary precautionary thought, illustrating the capacity to deal with route work and emergency cases. Otherwise, underestimating the severe condition may trigger serious issues in the system. In addition, it comprises legislative requirements on safety, security, and protection of marine environment (STCW, 2011). Unfamiliar equipment knowledge or inexperienced seafarers contributes to 32.69% of maritime accidents (Fan et al., 2020a).

CC relates to cognitive states and mental workloads. Lim et al. (2018) prove that most trainees have lower workload with the company of experienced masters, while the latter has the highest workload in the same situation because of their shared responsibility. Mental workload expresses the demand required by people to accomplish given tasks. A more mental workload is needed to complete the more sophisticated tasks. Therefore, such a concept has been widely applied to evaluate task performance and support the rational system design (Ngodang et al., 2012; Dijksterhuis et al., 2011). Experienced drivers have lower workloads than novices because they acquire more effective automation through practice (Patten et al., 2004). It illustrates that "inattention", "inadequate procedures", "observation missed", and "communication failure" influence human cognition in accidents.

3.2. Process phase – SA

Lack of SA is a critical cause of human errors referred to as CRM (Barnett, 2005). It is also related to the condition of distraction and using recreational drugs or alcohol. From the Marine Accident Investigation Branch (MAIB) 12–2016, the master, who lacked sufficient assistance, was unable to obtain and maintain the SA, leading to difficulties in identifying the hazards onboard and manoeuvring. It finally resulted in a grounding accident. Without SA, it usually takes problems for the seafarer to timely spot the vessel in trouble, even with sufficient data and records onboard. As stated in a collision accident report MAIB 28–2015, after a pilot's disembarkation, the bridge team had not monitored another ship's movement for 8 min due to the loss of SA. Even with adequate information, the master and the third officer failed to execute the proper monitoring. Therefore, it is essential for seafarers onboard to sustain the SA. In addition, the master's lack of SA can be attributed to psychological factors such as stress, and teamwork issues, including poor communication (MAIB 20–2017).

3.3. Process phase – TML

TML consists of supervision among the teamwork and social and cognitive support on various officers on duty. During the navigation, ineffective support and improper supervision reveal high risks. Working isolated makes operators vulnerable to hazards because of the workload pressure and onboard culture. It can be found in the MAIB 17–2016 report that the third engineer spotted the fuel leaking and intended to fix it without informing the chief engineer or the bridge Officer of the Watch (OOW). Because there was probably an absence of adequate communication among the team. More importantly, it was associated with isolated routine work, given the onboard culture. That is to say, the chief engineer's standing orders further condoned the situation of working alone. Evidently, they disobeyed the guidance provided in section 15.9.1 of the code of safe working practices for merchant seafarers (COSWP), and the code of safe working practices for merchant seafarers 2015 edition.

3.4. Process phase – COM

"Careless talk costs lives"(Winbow, 2002). The phrase illustrates the importance of effective communication and the severe risks if they go badly. Ineffective communications usually exist with cultural differences and language "barriers" which lead to misunderstandings among the crew. Research on Greek shipping shows that communication issues with multicultural teams are attributed to cultural incompatibility and insufficient training (Theotokas and Progoulaki, 2007). The study shows a significant difference in communication competence among groups of different educational qualifications (Fan et al., 2018). Chinese seafarers with tertiary education have better communication skills than those without it. Such an issue inevitably affects crew management and operation. From this perspective, communication is associated with culture management in maritime safety, improving team coordination and human performance in the perspective of human factors. Shipping safety can also be strengthened through appropriate technical support and communication for a master's command (Tzannatos, 2010).

3.5. Process phase – DM

Decision-making involves utilising information, knowledge, situational awareness, teamwork and communication to make rational choices. It relates to the process from receiving reliable information to the action made to execute commands. However, relying on a single data resource to make decisions introduces potential undetected errors or inaccuracies. It reflects the reliability of navigational aids and effective information exchange. In light of maritime pilotage, given imprecise information, pilots risk making inappropriate decisions without reliable navigational aids. Decisions to amend courses or speed need to be in accordance with accepted navigation practice (STCW, 2011). Adequate supervision and supports from the bridge team are beneficial for a practical decision.

3.6. Output phase – EQM, SO, SC, and PO

Lack of EQM competency, e.g., incorrectly positioning or ignoring alarm systems, contributes to human errors. Without updated and sufficient information, such human errors aggravate the situation. In addition, poor-quality data and falsified records hinder information transformation for rational decision-making in accidents. On the other hand, navigational indicators, e.g., working lights, are essential for seafarers to relieve mental overload. Furthermore, correctly using information from the equipment benefits seafarers' high standards of watchkeeping. It is also critical in the process of obtaining and maintaining a good SA in shipping.

SO includes ship manoeuvres and collision avoidance actions. To be specific, it means the selection of steering mode is appropriate given the prevailing weather, sea, and traffic conditions; manoeuvre signals are correctly used, and collision avoidance actions taken are under the International Regulations for Preventing Collisions at Sea and other applicable rules. Also, safe operating limits of ship propulsion, power systems and steering are not exceeded in normal manoeuvres.

SC represents the ability to amend and maintain a ship's course and speed through adequate information, sufficient knowledge, and corrections of errors in equipment or system. In addition, PO stands for being in accordance with contingency plans, cargo operations, handling of dangerous cargoes, cargo inspection, and pollution prevention actions. Besides, procedures and safe working practices to safeguard the environment, personnel, and the ship are always observed (STCW, 2011).

3.7. Machine sub-system, disturbance, and reference signal

Machine sub-systems relate to vessel conditions, devices, and ship ergonomics. It feeds updated information to the human's input phase. Regarding ship automation, new challenges are introduced by the increasing complexity of ship components and vessel modifications and the change in ship size. With innovative bridge design, it is inevitable to consider ergonomic impacts, such as a visual blind sector onboard and motion illusion during navigation.

The disturbance is considered as the effect of the relevant environmental and geographical factors, including sea, weather, fairway traffic, and noisy acoustic environment. As demonstrated in Fig. 2, the disturbance contributes to both human and machine sub-systems. A fuzzy analytical hierarchy process has been applied to assess the relative risk elements, and the appropriate safety levels of different ports in Korea are ranked (Pak et al., 2015). The results show that the most important factor is the weather. Lee and Kim (2013) analyse maritime traffic environment influential factors, indicating that visibility restriction is the most critical factor and traffic condition is the risk category with the most senior hierarchy. In addition, a vibrating environment and sea conditions have an effect on operation behaviours, containing tidal stream, current, and waves. It also induces the emotional response of operator and generates psychological effects in the human factor perspective.

The reference signal contains PP and RM. No detailed PP and the revised PP without approval are common issues in maritime accidents. RM reflects complying with regulations and management, which involves organisational factors. Maritime accident reports reflect that inappropriate and ambiguous codes, endorsements, regulations, procedures, instructions, formally published guidance, operation manuals, and requirements may contribute to human errors so as to induce sophisticated causal chains in maritime accidents.

4. Case studies

Two cases are selected from the raw accident reports from MAIB to demonstrate the feasibility of the dynamic human-machine system. These two cases have universal reference value and are highly related to human factors but without major technical failures, as shown in comprehensive reports. More importantly, these two accidents had been reported with all the details relating to the elements in the proposed methodology and hence are appliable for the demonstration purpose. They are also very representative as ship grounding and collisions are the two major maritime accidents in statistics. Furthermore, the proposed method is generic, and can be applied to analyse various maritime accidents involving human factors/errors. This is evident by the similar system in the other transport sector (Mansikka et al., 2019). However, in the maritime industry, although human actions contribute to 60.6% of marine casualties (EMSA, 2021), new solutions to the dynamic model between human factors and machines are yet to be effectively explored. The details of accident progress draw useful insights into how the system can aid in obtaining the claimed contributions in Section 1.

4.1. Grounding accident

4.1.1. Accident summary

There was a UK-registered ultra-large container vessel CMA CGM Vasco de Gama grounded on the western side of the Thorn Channel in the early hours of the morning on 22 August 2016 (MAIB 23/2017). After being handed over the con, the lead pilot ordered to increase the speed and change the course toward the Nab Channel. At 2300, the Vessel traffic services (VTS) called and provided updated information on vessel movements in the navigation area. As a response, the lead pilot sped down the ship. At 2343, both pilots had agreed to pass port-to-port when executing the passing manoeuvre with Cap Hatteras. At the same time, CMA CGM Vasco de Gama's speed was adjusted. After passing the small outbound container vessel X Press Shannon, the lead pilot ordered to increase the speed from 7.5 kts to 12 kts. At 0021, the lead pilot ordered the helmsman a series of courses to steer, which caused the container ship to a heading of 260°. Consequently, the vessel with a speed of 11.9 kts passed 0.25 nm north of the Prince Consort buoy. Then, the lead pilot ordered "starboard 10°", followed by full helm to starboard (35°) and increasing the engine to full speed ahead. When the vessel's rate of turn (ROT) dropped, the lead pilot planned to turn to starboard early and set the engine full ahead. Even the vessel entered the shallower water, the lead pilot insisted on keeping going. With decreasing ROT, the VTS officer called that the vessel was leaving the channel and alerted the tug skippers on standby to offer timely assistance. About 0.4 nm northeast of the Gurnard buoy, the vessel grounded.

The MAIB's conclusion is: "… the vessel was too far to the north when its turn into the Thorn Channel was commenced, and was unable to sustain the rate of turn required to stay within the dredged channel; the pilotage was not properly planned, the intended route was not charted, and key decision points, wheel over points and abort options were not identified …; neither the route plotted on the vessel's ECDIS and paper charts, nor on the Portable Pilot Unit (PPU) was achievable given the environmental conditions …"

4.1.2. Dynamic human-machine system analysis

The grounding of the container vessel CMA CGM Vasco de Gama was analysed using the dynamic human-machine system in Fig. 2. The input values are derived from maritime accident reports. They are converted into acceptable forms of risk factors with reference to the seafarer competencies based on CRM and STCW. The process stage is then followed to see how risk factors interact with each other by strictly following the accident process chain and the newly developed model. Finally, the appearance frequency of one risk factor will be counted as the output. If the value is the highest, the risk factor impacts the dynamic flow most. To illustrate causes and evolution of the accident, the partial sequence of failures and violations are given in Fig. 3. During the accident process, the communication issue occurred three times, at events 2, 6, and 12, separately.

Then, the analysis in a dynamic human-machine system is demonstrated in Fig. 4. The superscripted numbers refer to the accident process chain and system components of the human-machine system. The human input and output phases are separated among the lead pilot and master.

In the beginning, there was no adequately planned pilotage plan[1]. After handing over the con from the master to the lead pilot, the provisional pilotage plan was not adequately reviewed or amended to reveal the lead pilot's intention. The lead pilot's intention to manoeuvre around Bramble Bank was not effectively communicated with team[2]. In addition, the bridge team's responsibilities in the navigation were not identified clearly[3]. Therefore, the lead pilot executed the turn[4] without teamwork, which did not obey the port's guidance. Due to the lack of a clear pilotage plan, the master and the team were unable to monitor the lead pilot's actions and the ship's course, which created task demand loss for the master[5]. Evidently, the bridge team lacked effective information exchange and communication[6], resulting in the failure to share the same mental model between the master and lead pilot. Then, the ECDIS was not correctly used by the lead pilot[7]. As a result, the accurate pilotage routes were not charted; equipment was not set up; the display screen setting was not appropriately selected[8]. Given the disturbance of environmental conditions, i.e., the spring flood tide and the wind, the vessel's ROT began to drop[10], not as expected. It caused the isolated decision maker, the lead pilot, to decide to turn to starboard early and set the engine to full ahead[11]. Although the master had shown a similar

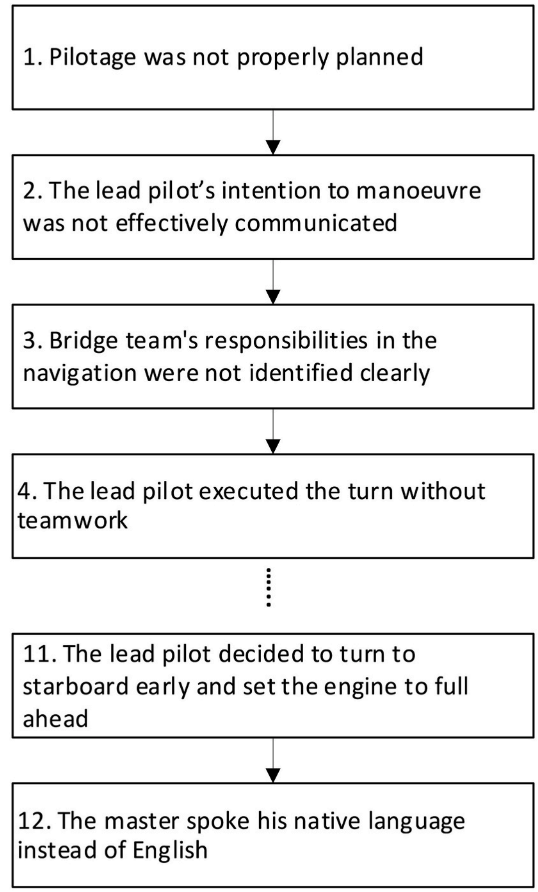

Fig. 3. The partial sequence of events for the grounding of CMA CGM Vasco de Gama.

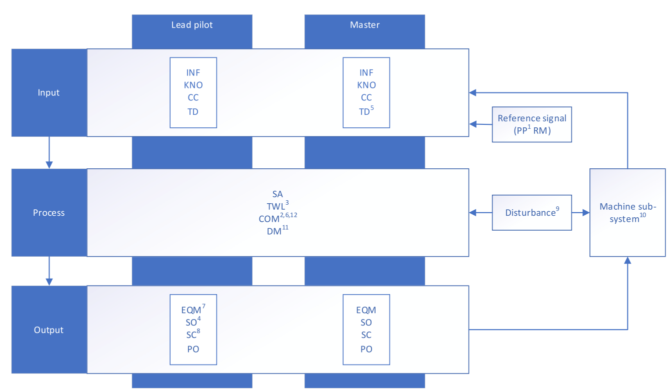

Fig. 4. Dynamic human-machine system for the grounding of CMA CGM Vasco de Gama.

concern to the OOW, he spoke his native language instead of English[12]. Then the vessel grounded on the gently shelving seabed. The lead pilot tried to correct the vessel's trajectory but was unsuccessful.

The human-machine system model shows that the lead pilot was lack of EQM, SO, and SC competencies; the master was lack of TD competency; both of them had a deficiency in TWL, COM, and DM. Among them, communication issues occurred three times during the accident. First, it reflects the communication problems with the bridge team at the early stage, where the lead pilot's intention was not revealed. In the middle of the navigation, the lack of effective information exchange deteriorates the situation by the loss of a shared mental model between the master and pilot. Finally, when making decisions, the communication issue arose again because the master spoke native language, so the OOW did not receive his concern about the vessel's turn and engine setting. Although communication is an essential risk factor in many maritime accident reports, it should be noted that communication outweighs other competencies in this single case due to the high frequency of its occurrences (three times) in the analysis by the dynamic human-machine system. Therefore, one of the main contributions of the new system is that it can effectively aid to identify and prioritise the human factors contributing to a maritime accident by analysing their interactions. Therefore, the developed system opens a new door for human factor analysis and investigation, which cannot be revealed from the accident investigation report.

4.2. Collision accident

4.2.1. Accident summary

The Panama-registered car carrier City of Rotterdam and the Danish-registered ro-ro ferry Primula Seaways collided on the River Humber on 3 December 2015. When the master and pilot exchanged information, the master showed the pilot the vessel's centreline with a length of cord on the centre window. They discussed the wind effect, and the pilot anticipated a high drift throughout its passage. At that time, the pilot observed the vessel's position by eye, and through an electric chart system and a port radar display. The pilot of City of Rotterdam changed the vessel's heading from 125° to 095° in 5° increments to manoeuvre the ship further to the south. While Primula Seaways was in clear sight, with 2.8 nm apart from City of Rotterdam (heading 105° at 12.2 kts). When the two vessels were 0.97 nm apart, the pilot of City of Rotterdam confirmed the vessel's heading and ordered it to steer 115°. During the VHF exchange, Primula Seaways' master ordered to reduce the speed to 0.94 kts with the engine "half ahead". Then "starboard 20" was given by City of Rotterdam's pilot, followed by "midships" then "135°". The master intervened, and the pilot explained that both ships were experiencing drift. Then, primula Seaways' bridge team selected manual steering and applied full starboard helm and full astern engine, because they spotted that City of Rotterdam was not possible to turn starboard as timely as they expected. At the same time, City of Rotterdam's pilot gave an order of 150°, and the helmsman executed 5° of starboard helm, where two vessels were 0.27 nm apart. City of Rotterdam did not reply to the VHF radio exchange, and the master ordered "midships" followed by "hard to port". At last, two vessels collided after 14 s.

The MAIB's conclusion is: "… the collision stemmed from City of Rotterdam being set to the northern side of the Bull Channel by the wind and the tidal stream followed by the distortion of its pilot's spatial awareness due to a 'relative motion illusion' …; City of Rotterdam's bridge team's over-reliance on the pilot, and its lack of effective monitoring of the vessel's progress, were evidence of ineffective bridge resource management …"

4.2.2. Dynamic human-machine system analysis

The collision between these two ships was analysed using the dynamic human-machine system. A similar analysis was conducted to investigate how the accident occurred from its initial event to the final casualty. Then, the dynamic human-machine system is demonstrated in

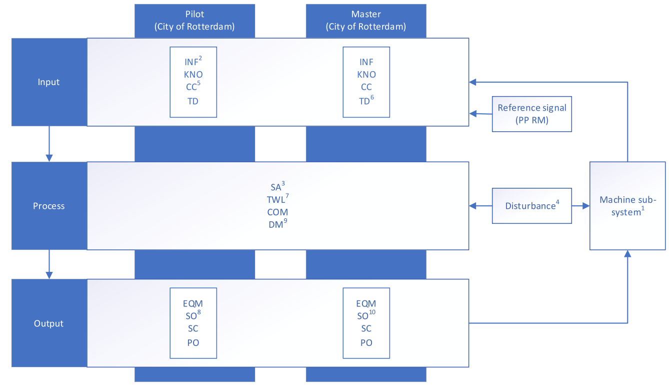

Fig. 5. Dynamic human-machine system for the collision between City of Rotterdam and Primula Seaways.

Fig. 5. The human input and output phases are separated among the pilot and master of the City of Rotterdam, because the Primula Seaways related deficiency was only about more speed reduction.

Initially, the car carrier City of Rotterdam was of an unconventional design, which caused "relative motion illusion" when the pilot looked through an off-axis window on the semi-circular shaped bridge[1]. It means that the pilot received ineffective information and thought the vessel was on the passage in the direction he was looking[2]. Furthermore, such a situation led to the distortion of pilot's SA[3]. Under the circumstance of the wind and tidal stream, the illusion was compelling in the dark without any visual clues[4]. Moreover, this situation increased the cognitive costs for the pilot to transfer between different frames of reference[5]. The psychological effects of the relative motion illusion hindered the pilot's ability to reconcile the headings. In addition, it was evident that the master left the responsibility mainly to the pilots and did not monitor the vessel's position[6]. There was a deficiency in the bridge teamwork that the team over-relied on the pilot and did not challenge the pilot's actions even Primula Seaways and the VTS showed concern about the vessel's position[7]. As a result, when Primula seaways selected manual steering and applied full starboard helm, while the pilot of City of Rotterdam ordered "150°"[8] and the helmsman applied 5° of starboard helm. Therefore, the master had to intervene[9] and ordered "midships" followed by "hard to port"[8], but it was too late to be effective. Two vessels collided in the end.

The human-machine system model shows that the pilot was lack of INF, CC, and SO competencies; the master was lack of TD and SO competencies; both had a deficiency in SA, TWL, and DM. The circumstance of the wind and tidal stream impact the 'relative motion illusion' in the dark and influence the seafarer's SA. On the other hand, this disturbance increases the cognitive costs of the pilot through the machine sub-systems. Therefore, it shows that competency elements influence each other through casual relations and feedback from machine sub-systems. The seafarer competencies as components in dynamic human-machine cooperation help rationalise human factor evaluation in the maritime closed-loop system. Furthermore, it can significantly help improve the training effectiveness and efficiency by targeting the prioritised competencies against different scenarios.

4.3. Theoretical and policy implications

The proposed model develops a new dynamic approach to analyse seafarer competencies in a closed-loop system. There are theoretical and practical implications. The theoretical implications are 1) analysis of the interaction of seafarer competencies in a closed-loop system based on CRM and STCW; 2) it fulfils the gap in the prioritisation of seafarer competencies by in-depth investigation of maritime accidents (shown in two cases); 3) a new dynamic system to compass the seafarer competencies and their interaction could shift the maritime accident investigation mechanism in future.

Furthermore, the managerial and policy implications can be seen by different stakeholders such as accident investigators, maritime authorities, manufacturers, and Maritime Education and Training (MET) associations. Because risk factors in maritime accidents can be explained in terms of significance and impact. The significance means high occurrence frequency in historical records, while the impact reveals one factor occurring many times in one single accident. The former is defined as significant risk factors, while the latter is named as the factors with the most impact on a single accident. In the current literature, the former is much better addressed compared to the latter. This paper is developed to investigate the impact of risk factors in one single maritime accident. Its significance is also evident by the fact that although the occurrence likelihood of some risk factors in traditional statistics is not high, they are critical to certain marine casualties in which they appear many times to affect the accident process from an initial event to the final fatalities, such as the communication issues. Previous models can identify significant risk factors in terms of the frequency of a single factor occurring in many different accidents. However, the developed model can address the risk factors with the most impact regarding times of a single factor occurring in a single accident. That is to say, by measuring the occurrence of a risk factor in a single accident in the proposed model, one will be able to identify the risk factor(s) with the most impact on the accident occurrence. The closed-loop system enables the transmission of failure events between input and output of sub-systems, so the model can count the frequency of each risk factor, representing their impact on maritime accidents. It helps find the clue on significant causes of accidents. Maritime safety administration and authorities can benefit from the proposed model to amend the regulations for safety at sea, with a particular concern on MASS. Compared to the existing STCW, the new code and rules aimed at advanced ships will learn the lessons from previous accidents and be developed according to summarised competencies. Moreover, when the manufacturers design new MASS, they can use the model result to optimise autonomous components and HMI to be more user-friendly and reliable. It will significantly improve the current ship ergonomics and encourage human-machine cooperation. In addition, MET and BRM aim to prioritise competency training against different scenarios and seafarer qualifications. It better clarifies various classifications of risk factors, such as ships, environment, humans etc., consolidating human performance in ship sub-systems. The competencies that severely impact the dynamic system should be highlighted in training and prioritised to cope with maritime risks.

5. Conclusion

A new model to analyse the dynamic human-machine system in the maritime sector is constructed based on CRM/BRM and competence in STCW code. It comprises human and machine sub-systems in a dynamic flow. Such a closed-loop system illustrates systems' vulnerable points and evaluates the causal chain process in accidents. A new tool to analyse seafarer competencies is proposed to rationalise human factor evaluation in the maritime closed-loop system and reflect the dynamic human-machine cooperation process. Two case studies are conducted to demonstrate the feasibility of the new model and aid to produce a new analysis perspective to investigate human factors in maritime accidents. The results help explore the adjustment of maritime training to support ship automation and provide policy implications on risk management for manned and autonomous ships.

The dynamic human-machine system enables the root cause analysis and its evolution with humans, vessels, and the environment. Specifically, as a root cause, deficiencies in the system do not lead to inevitable catastrophes but may trigger a chain of failures in other phases. The root cause is essential but not mortal sometimes. How root causes impact other risk factors in the closed-loop system is worth investigating. Therefore, the interaction between different phases in the proposed model reveals how seafarer competencies influence the system's effectiveness.

The first case study of grounding shows that the primary causes are human factors. It is evident that complacency and overconfidence of the master and port pilots contribute to human errors resulting in accidents. Measuring the occurrence of a single element in the closed-loop system helps redefine the impact and importance of risk factors in maritime accidents. Therefore, it provides a new perspective for human factor analysis, which cannot be revealed from the current investigation report. The second case study of collision implies the severe deficiency in City of Rotterdam and discloses the ineffective human-machine interactions in the accident. The proposed human-machine system identifies the effects of ergonomic issues onboard ship bridge on cognitive costs and human behaviours. In addition, the seafarer competencies as components in a dynamic human-machine system help rationalise human factor evaluation in the maritime closed-loop system. Therefore, accident investigators can better identify the most impacting risk factors. Maritime safety administration and authorities can utilise it to amend the codes for marine safety. Aiming at advanced ships and MASS, the new code and rules based on STCW can benefit from the proposed model to redefine competencies. Furthermore, it can help improve the training effectiveness by targeting the prioritised competencies against different scenarios. MET and BRM can prioritise competency training against different navigation scenarios and seafarer qualifications.

The proposed model can support competency importance analysis by doing case studies. It pioneers the analysis of seafarer competencies based on CRM and STCW. The results help evaluate the causal chain process in accidents and monitor human performance in safety-critical systems. In addition, dynamic features of the system can be used to adjust the level of automation with human-machine interfaces in advanced ships. Although two cases are analysed in the study, the findings aid in illustrating new insights into human reliability and open a new dimension on seafarer competency analysis. A new dynamic approach to compass the seafarer competencies and their interaction will help rationalise human factor evaluation in maritime accidents. It should be noted that the proposed model may be complemented by further exploring the relationships between competencies in each phase. The quantitative analysis will be conducted with competency data available in future study. Analysis of more historical accident cases will expose different importance regarding their influence and impact. In future, one can use the developed model to generate insightful findings against different maritime accident types (representative ones) and measure how the competency element plays a role in each type of accident.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zaili Yang reports financial support was provided by European Research Council. Zaili Yang reports financial support was provided by EU Framework Programme for Research and Innovation Marie Curie Actions.

Data availability

Data will be made available on request.

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