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Since 2003, the International Maritime Organization (IMO) has emphasised the need to address and integrate ergonomics knowledge in a concerted manner. However, there is little guidance on the application of this knowledge in the design of merchant vessels. Utilizing a mixed methods approach, the paper identifies the need for crew-centered design (CCD), highlighting the importance of using concepts derived from Human-Centred Design (HCD) to be able to design work spaces and operational procedures that facilitate the work of the crew on board. Drawing upon results obtained from accident analysis (utilising the Technique for the Retrospective and predictive Analysis of Cognitive Errors - TRACEr) and 24 semi-structured interviews, this paper identifies areas in which it could be potentially beneficial to integrate end-users in the design of ships and shipborne operations. This paper further discusses why and how concepts rooted in HCD could be used to improve maritime workspace and interface design, as well as the design of procedures and shipborne operations. However, due to the specifics of the maritime domain, the authors propose that there is the need to expand the HCD perspective, making the design not only fit a single user, but to fit the crew as part of a maritime socio-technical system. The paper discusses that the case for CCD is imperative in the interest of safety, efficiency and even makes economic sense.

Practitioner Summary: This paper utilizes a mixed methods approach comprising accident analysis and 24 interviews with seafarers and a company representative, to make a case crew-centered design (CCD). CCD is based on concepts derived from human-centered design (HCD) and expands these to encompass the whole crew on-board and not only a single user. Identification of the need for HCD is a prerequisite to the iterative human-centred design cycle (ISO:9241-210 2010) which enables HCD practitioners to develop solutions with the end goal to satisfy user and organisational requirements. This paper identifies the need for undertaking CCD in the specific ship-board context, thus linking CCD with HCD.

Keywords: Crew-centered design (CCD), Human-Centred Design (HCD), human element, and accident analysis, TRACEr

1. Introduction

The maritime transport system forms the backbone of the world economy with nearly 90% of the international world trade being carried out by the sea (ICS). There has been a considerable growth in international seaborne trade over the past decades and the world fleet has consequentially expanded to meet the growing demand for shipping (UNCTAD 2014). More than just a mode of cheap transport, maritime transport is a transnational intricate linkage of complex supply chains between the world economies (Bonacich and Wilson 2008).

Vessels within the maritime transportation system can be considered as complex socio-technical systems comprising interacting social (crew and shipping operators) and technical elements (equipment, machinery and technology) (Praetorius and Lützhöft 2011).

The human-machine interface has featured in serious maritime casualties that caused irreparable loss to life and property. One example is the collision of the *Andrea Doria* and *Stockholm*. It is, but one example of how the technology introduced to improve safety was used to push for more efficiency in terms of proceeding faster. The two vessels had seen each other, but still collided (Perrow 1984). The role of automation has been identified in the grounding of the *Royal Majesty*; it has been argued that automation alters the task it was intended to support, creates new errors paths, shifts consequences of error further into the future and delays opportunities for error detection and recovery (Lützhöft and Dekker 2002).

While often referred to as the source of error (Baker and Seah 2004), the perspective on human operators working on board of merchant vessels has changed through the past 15 years. The IMO has increasingly tried to emphasize the role of the human element as a complex and multi-facetted aspect, which often represents the last safeguard to maritime safety. Therefore the organization's human element vision has been adopted and several circulars have been provided that highlight the need to support the mariners on-board by integrating ergonomics in the design of maritime equipment (IMO 2003, 2006a, b, c)

However, while a large body of scientific literature addresses decision-support systems and interface design (Porathe et al. 2013; Benedict et al. 2014), there is a lack of research with regard to how to integrate end-users, mariners, into the design of work spaces and procedures in maritime operations. This article presents results based on the work conducted within the CyClaDes project. CyClaDes stands for *crew-centered design of ships and ship systems* and aims to identify, locate, apply and disseminate knowledge on how to best integrate end-users in the design of maritime systems to create safe, efficient and resilient maritime operations. The project is funded by the European Commission under the 7th Framework Programme and has a multi-disciplinary consortium comprising 14 partners drawn from the academia and industry.

This article attempts to show that concepts derived from HCD can be extended to fit the specific settings of the maritime domain, and that this offers an opportunity to make operations and workspaces that support the work on-board, safe. Results from an accident analysis conducted with the TRACEr taxonomy, as well as the results from 24 semi-structured interviews (with 23 mariners and 1 company representative), will be used to highlight how poor design compromises safety and efficiency and can even have an economic cost attached. The paper concludes by presenting the concept of crew-centered design and discusses how this can be used to improve the preconditions for safe and successful maritime operations.

2. Background

Human-centered design (HCD) is an approach to the design of interactive systems and aims to make these more usable through the application of ergonomics and usability knowledge. It advocates an interactive design process focused on understanding the user, task and environment through end-user involvement throughout the whole process. The output of the HCD process are systems that have the potential to increase the overall system performance, for e.g. amongst others, decreased stress or discomfort, increased usability, or being easier to use in terms of a lesser need for training. The iterative HCD cycle adapted from (ISO:9241-210 2010), is presented in figure 1 and the HCD cycle and usability can be integrated with the *general design diagram* (ship design spiral) (Evans 1959) as appropriate.

One goal of the HCD approach is to increase a system's usability. Usability is defined as *the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context* of use (ISO:9241-11 1998). It emphasizes the need to consider, not only efficiency and effectiveness, but also the specific context in which a product's use or process is situated in.

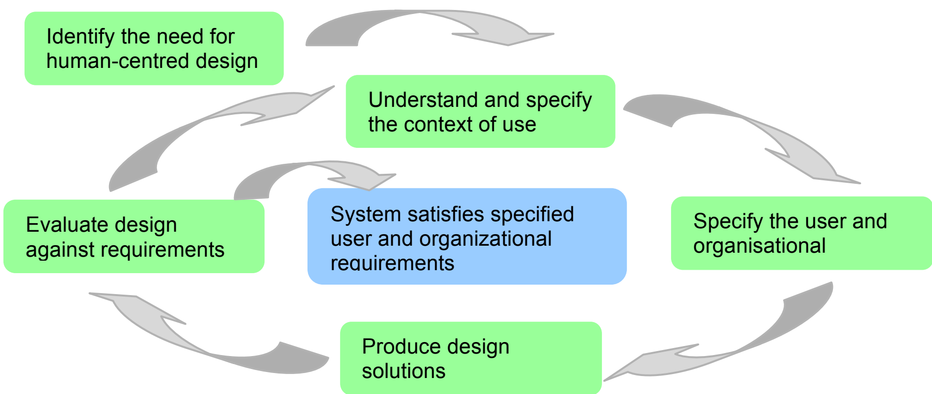

Figure 1. The human-centred design cycle (adapted from: ISO 9241-210, 2010)

Earthy and Sherwood Jones (2010) analyse standards for HCD in the context of ship systems. They suggest that a human-centred approach within the design process has the potential to address the human element quickly and effectively. Success factors of User-Centred Design (UCD) in shipping are explored utilising focus groups by Costa and Lützhöft (2014). The meanings and the perceived benefits of UCD are categorised and presented by the authors, who further state that importance of the approach to end users, can serve as an incentive for shipping companies and designers to adopt the same. Bligard et al. (2014), utilised 2D and 3D models as mediating tools to elicit end user feedback during the workplace design process. The authors found that diverse model types allow for different levels of reflection and interrogation of design by the prospective end users. The authors further add that mediating models to obtain end user feedback on design in a cost effective manner can greatly benefit design teams.

Petersen et al. (2011) note that academic literature lacks accounts of systematic application of maritime human factors. The authors go on to further state that with limited market demand and the lack of rules, the initiative for application remains largely with individual organisations. An economic case for design in shipping has been made by Österman (2012) who argues that the design case needs to be strengthened by highlighting economic gains for ship operators in addition to highlighting the design contribution to safety and efficiency (also see Österman 2013)

Reducing crew levels, increasing levels of automation, computerisation and administrative workload in the on-board environment have altered traditional roles at sea; Ljung (2010) suggests a functional approach towards achieving optimised manning with the integration of flexibility. The author discusses *functional flexibility* and *working time flexibility* and argues that with the combination of functional flexibility with job enrichment and continuous professional development with working time flexibility, the ground for a win-win situation between seafarers and shipping companies can be laid. The author further argues for a holistic approach when strategizing for change. For on-board work organisation and function-based manning, also see Ljung and Lützhöft (2014).

3. Research methodology

A mixed methods approach comprising accident analysis and semi-structured interviews was utilised in the study. In the first phase, the accident analysis of 129 publicly available accident investigation reports was carried out utilising the TRACEr taxonomy for the coding and subsequent analysis of the accident data with the aid of the MaRiSa database (2013). TRACEr was developed by Shorrock and Kirwan (2002) for research within Air traffic Control. TRACEr was chosen for the accident analysis in the maritime domain as it addresses the human-machine interface, is both retrospective and predictive in its outlook and addresses error recovery. TRACEr has a modular structure comprising eight inter-related taxonomies. These taxonomies can be divided into those which describe the context of the incident, those that describe the cognitive background of the production of an error and those relating to the recovery of the incident. TRACEr needed to be adapted to the maritime context for the purpose of the study (see figure 2).

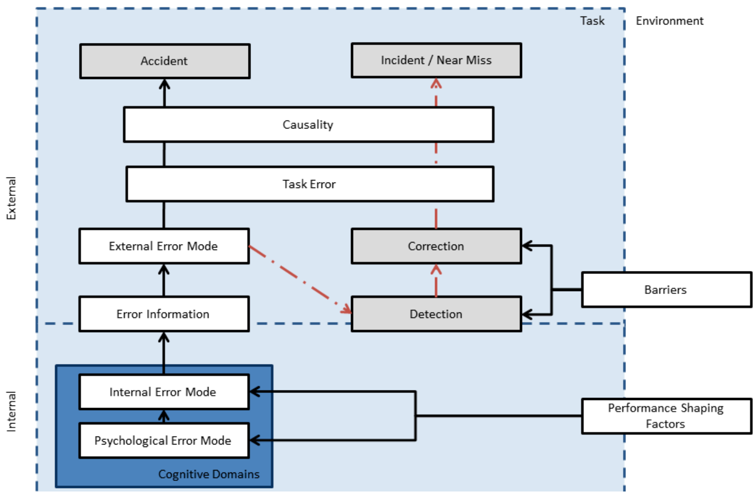

Figure 2. TRACEr Framework adapted for CyClaDes

In addition to the accident analysis, the study involved semi-structured interviews with 24 participants (23 seafarers and 1 company representative). Of the 23 individuals with seafaring experience, 1 was a female deck cadet and 22 were male participants. Of the 22 male interviewees, 18 were from the navigation department and 4 from the engine department. The company representative interviewed was also male. A semi-structured interview guide was designed for the study which focused on the design of spaces, equipment and operations on-board. Participants were encouraged to share instances where they believed the design of equipment and/or space did not support their work and was not fit for purpose and accidents which they knew of, in which design played a role. Each interview lasted for 45 minutes on an average.

4. Results

4.1 Accident analysis

Two-thirds of the 129 accidents coded involved human-machine interaction. The largest category of accidents on-board is personal accidents (44%), followed by collisions (29%), grounding (15%) and fire (4%) in descending order (see figure 4). Accidents and consequential injuries to personnel feature prominently in the analysed data. Underlying issues to the accidents reveal the role of design or lack of it, in shipboard equipment, space design and layout. The highest number of accidents were attributed to the bridge (50%), followed by the deck (38%) and the engine room (12%). This finding is unsurprising as the bridge is the command and control centre of the vessel and most accidents have been attributable to personnel, decisions and equipment on the bridge. In 66 % of the cases there was mitigated loss in which the vessels regained operation while in a substantial 34% of the cases there was a total loss of the vessel.

A high, 19% of errors in the reported accidents are attributed to the Captain, followed by the Chief Officer (14%), Able Bodied Seaman (AB) (9%) and Pilot (8%). The tasks which led to the task errors are navigation (23%), followed by traffic monitoring (18%), cargo work (18%), maintenance work (15%) and mooring operations (4%). The user materials involved in the task errors are identified in the data as radar (64), loading devices (13), mooring equipment (11), stairs, ladders (11), steering panel (11), engine room controls (10), Very High Frequency (VHF) radio (10) etc. in that order.

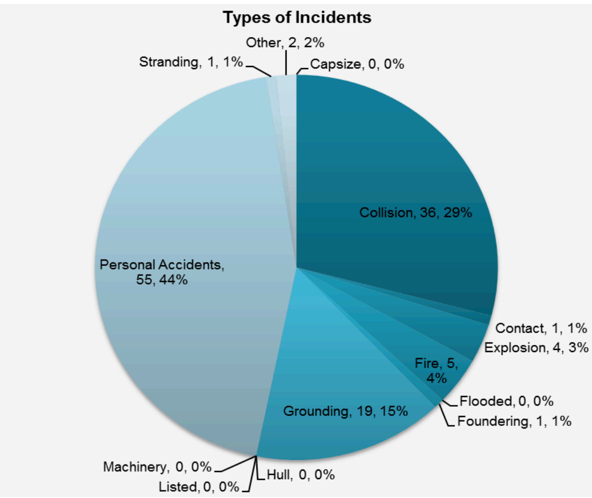

Figure 4. Type of accidents

4.2 Results of interviews

This section presents the results of the semi-structured interviews. Each of the 24 interviews was transcribed verbatim and the data sorted thematically. Across the board interviewees shared examples of experiences of poor usability on-board, in which the equipment and/or the layout was unfit for purpose and did not support the task/operation undertaken by the seafarers. In relation to the on-board work environment, it was further stated that the seafarers do not have the option to stop work as they have a limited manpower and their work environment is unique in the sense that they live and work on-board the ship for the duration of the contract and unlike other shore-based workers, do not have the option of returning home at the end of the day's shift. By and large, as far as possible the seafarers tended to figure out local solutions to deal with the usability related constraints and continued their work. Two quotes from respondents given below are illustrative of how they perceive design and shipboard work. The responses of the seafarers point to the perceived immutable fixed character of on-board design which they largely could not alter and they needed to work with what was made available to them.

"I tend to overlook the design … my main impression is that when you see a problem, you sort it out"

"You cannot change the design"

Location of equipment and/or machinery, space for crew movement and access to the same is vital for seafarers in their on-board operations. A respondent observed that an increase in cargo carrying capacity restricted the space available on container ships. Adequate space between stowed containers with catwalks would be supportive in the work. However he further added that it appeared that money appeared to be a deciding factor as the company focus appeared to be more on cargo carrying capacity that generated revenue rather than adequate crew access. On the issue of ladders, the same respondent noted that vertical ladders caused fatigue and access points, ladders and walkways could be improved with good design.

Another respondent stated that shipping yards did not consider that once something is fit, it would need to be opened, cleaned, maintained and repaired, and on-board personnel will not have access to similar advanced tools as the shipyard. According to the respondent it would be useful to have dedicated cleaning areas between floors, where you can open the panel and isolate sections and carry out cleaning of drains and pipes if required. Regarding pipes and manifolds, he added that the designers and builders should consider how users will open the pipe, repair it or change the pipe if required. The respondent further added that at times 5-6 pipes are put in a bundle on top of one another and to get to one pipe, one ended up opening and disturbing a lot of others. It would be preferred if the pipes could be spread out but that would take space. The present location of the pipes was rather low according to the interviewee, who felt that near the bottom plate, it was very corrosive for the pipes. In relation to the pipes, the interviewee spoke of uneven walkways on tankers that move up and down in relation to the layout of the pipes and was stated to be a hazard in the dark.

Each time seafarers join a ship, they could be faced with different design solutions on-board with respect to space layout, equipment and operations. Standardisation of equipment was one of the key concerns for interviewees who felt that fleet wide, within a company there should be standardised equipment as that has issues for safety, efficiency and re-familiarisation training. A respondent added that if one is aware of one's next employment on a particular class of vessels, then one could read about the equipment prior to joining and familiarise oneself.

Endemic *'light pollution'* was identified on the bridge by the interviewees as it impacted visibility and could impact safety. Display visibility and customisation of monitors/screens was considered very important by the respondents and they wished to be able to appropriately adjust the light settings for each. Availability of suitable dimmers for the bridge equipment would be viable solutions.

Alarms were considered extremely important and intelligent alarm management systems were the need of the hour on-board. On the issue of alarms, respondents noted that sometimes there were too many of them, for instance from the ARPA due to sea clutter, in which case there was the tendency to turn the alarms off and not to use them. The tediousness of the bridge watch keeping alarm which required to be physically turned off, prompted one Captain to tell the crew to turn it off. Alarms have been introduced to promote safety on-board but can be an irritant and unsupportive of the work on-board due to poor usability.

Mooring operations were considered dangerous by almost all of the respondents and suggestions were made to improve the design of mooring winches, windlass, rollers and location of the bollards on the deck to avoid obstruction. The line of sight was considered important in dangerous mooring operations and it was suggested that the location of the mooring winches, windlass etc. should be such that the person can see and have an overview of the operations. Due to limited manning, one respondent suggested hands free communication during critical mooring operations. An interviewee recounted an incident of a fatality during mooring operations in which design appeared to have played a role. The ship had additional mooring controls far up front so that the individual could see over the flair; over the gun valve. There was no protection in this exposed position and the officer continued to heave and make the rope tight -

"The rope parted … like a sword… and then they saw the chief officer standing there without the head…they found his head two holds away."

Rigging the pilot ladder is an important aspect for pilot boarding operations. One interviewee felt that the crew found it difficult to do it safely in inclement weather and there have been instances of individuals going over-board. He suggested that an improved mechanism should be put in place which could be used to lower and retrieve pilot ladders without risk to crew and further added that CCTV for the deck area would be useful for monitoring the space. Adequate stowage for pilot ladders and securing equipment at a suitable location on the deck is desired to prevent ladders from wear and tear.

Emergency drills involving life boat testing was also a cause for concern for some respondents. One recounted a fatality during lifeboat lowering when one clamp opened and the other didn't and the lifeboat went vertically down and the person inside suffered an impact to his head and died of brain haemorrhage. The interviewee said that either both clamps should open at the same time or none should open but it should never be the case that one opens and the other doesn't. The interviewee further added –

"No one dares to sit inside the lifeboat while dropping it. The main aim of the free fall lifeboat is you sit inside, then you use the hydraulic jack to release the gear and it goes back, but the impact will be too high and you are not well secured. You have belts …you have your head straps here, but it is so designed that it never fits you. It is too high or it is too low. So it never suits you."

Navigating officers mentioned the following equipment for improvement – *Automatic Identification System* (*AIS), oily water separator (OWS), gangway, pilot ladder, echo sounder, electronic char display and information system (ECDIS), display interface, mooring winches, windlass, hatch covers, alarms, pipes and manifolds.* With respect to equipment characteristics, respondents considered the following important – *standardisation of equipment, easy operation, display visibility in different light conditions, customised display options, availability and adaptability of alarms, location of equipment and labels.* With respect to essential characteristics of bridge layout, they preferred *location of equipment, sufficient space for work, appropriate lighting arrangements* and *line of sight*. For deck equipment, strength of equipment was important and for deck layout, *markings and signage* and free from obstructions was important. Interviewees considered ballasting operations, mooring operations, cargo operations and navigation in restricted and/or congested areas as important.

For the engine department interviewees, maintenance is a very important part of their daily work on board. The location of machinery/equipment/valves/pipes that require maintenance should be easy to access and support the work of the engineers. Largely things are difficult to access. In one instance the platform needed to be opened to reach the pipe and it would be useful if the pipes were a little higher. The local solution devised was to make a sign/label identifying the location of the valve and the connection of a long spanner so that no bending was required to open it. In connection with a leaking generator, it was difficult to replace the platform below the generator as it was difficult to lift and align the 500 Kg platform. In case of breakdown, portable replacement and easy dismantling of accessories should be considered in design.

Remote monitoring was considered useful by engineers who believed that all equipment should also have remote controls in addition to the equipment panels. The remote device can be kept in the engine control room and other colleagues can communicate regarding the situation in other parts of the engine. During bunkering operations, the remote monitoring of the tank levels was found to be very useful. Monitoring vital parameters remotely from the cabins was also considered useful for ships designed for unmanned engine spaces.

Starting the generators with heavy fuel oil was a concern in cold countries for an interviewee, where due to the low temperatures the generators would not instantly start. The poor design included only one heater for three generators and the generator closest to the heater started but the generator farthest from the heater could not start. In order to start the generator at the far end, the interviewee and his colleagues continuously needed to give a kick to the reducing valve thereby damaging it and necessitating its replacement. A small heater had been provided to save energy and it resulted in the reducing valve of the generator getting damaged. This has attendant economic costs of replacing damaged machinery/equipment.

Engine room operations are extremely hazardous. One fourth engineer recalled that in his company he was aware of as many as 3 fatalities in connection with the purifier. One engineer had forgotten to put the locking knot in place and as there was no alarm alerting him that a crucial step had been missed. The interviewee further said that the purifier should not have started without the locking knot in place.

"It started without the locking knot and purifier has something like 200 blades moving at 10,000 rpm, it came off. So it is like the blades come flying everywhere so it cut... It is like a cutting a person up… if you have forgotten to put a locking knot, it is very small. You may forget to put it. So there should be an automation that if you forget to put it, the purifier should not work, should not start and give an alarm."

The interviewees from the engine department wished to improve the purifier, ballast water pumps, generators and increased access to communication equipment in engine room spaces. The characteristics considered important by interviewees regarding engine equipment were: *easy operation, maintenance, replacement of spare parts, easy access, suitable location of equipment and controls, easy monitoring vital parameters, availability and adaptability of alarms and equipment labels*. In terms of the characteristics of engine room layout, the interviewees mentioned *sufficient space for work, temperature and noise*. It was noted that the problem of noise was more acute on smaller vessels and not in big vessels as steady equipment noise was considered a sign of well-functioning equipment. For the engineers, key operations were ballasting, bunkering, maintenance work, working with power generation equipment like the generators and monitoring vital parameters.

The main obstacle to design and usability was 'money' as perceived by the shipping company owner.

5. Discussion of results

The accident analysis (section 4.1) shows that poor design has a role to play in accidents. The type of accidents (personal, grounding, collision, fire etc.); on-board spaces to which accidents are attributed (bridge, deck and engine room); user tasks involved in accidents (navigation, maintenance, cargo work etc.); involved user materials (radar, loading devices, mooring equipment etc.) highlight the areas where CCD and usability can make a positive contribution to safety. The accident analysis makes a case for CCD with respect to the safety of operational work, life, property and the environment.

Unfit for purpose and poor usability is a key finding throughout the interview data. Seafarers regularly compromise, and work with poor design on-board. In several examples, the equipment/machinery/space has been identified as unsuitable and unsupportive of the crew; and poor design does not lead to effective and efficient operational performance, and is dissatisfactory in the context of use. Iterative HCD (ISO:9241-210 2010) and usability (ISO:9241-11 1998) need to be integrated in ship design (Evans, 1959), and crew involvement should be sought from the beginning to achieve usability (see Earthy and Sherwood-Jones 2010; Bligard et al. 2014). Personal injuries, fatalities and damage to equipment due to poor usability, come with attendant costs and contribute to bolster an economic case for design as put forth by Österman (2013).

The crew on-board undertake diverse tasks with incumbent functions – navigating, traffic monitoring, ballasting, mooring, bunkering etc. The tasks cannot be performed safely, effectively efficiently and satisfactorily due to poor design support. Function based, flexible manning with continuous professional development could be considered by shipping operators to promote safety, contribute to the design of improved shipboard operations, optimise available resources and support the crew as they serve on-board different vessels in the company fleet during their seagoing career (Ljung 2010; Ljung and Lützhöft 2014)

Costa and Lützhöft (2014) highlight the importance of design for end users and state that it could serve as an incentive to consider design, while this paper provides empirical data to make the case for CCD.

6. Conclusions

HCD is generic and focuses on the human in the design process. The authors draw upon HCD and usability, and propose the expansion of HCD to encompass the whole crew of the ship and take a crew-centric design focus with respect to ship and operational design, with CCD. Shipboard operations like mooring, involve several crew members at once and CCD could address the unique and complex in-situ operational context on-board. A ship has the distinction of simultaneously being the workplace as well as the leisure space for crew for the duration of their contract; crew work and live there; and to support them in their work and life on-board, HCD would be limiting and therefore an expansion of it to embrace the crew with CCD is proposed.

Acknowledgements

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