

# DESIGNING EFFICIENT AND SAFE MACHINERY SPACES FOR MERCHANT SHIPS: A HUMAN FACTORS APPROACH

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*In 1998, the IMO's circular MSC/Circ.834, entitled "Guidelines for engine-room layout, design and arrangement", set out the first principles for the integration of health, safety and ergonomics in the design and arrangement of the machinery spaces onboard ships. How can new development based on these guidelines improve efficiency and safety in machinery spaces?*

**KEY WORDS:** Machinery spaces, Engine room, safety, ergonomics, human factors, human-machine interaction, user feedback, user-centered design, health and safety.

## INTRODUCTION

In 1998, the IMO's circular MSC/Circ.834, entitled "Guidelines for engine-room layout, design and arrangement" [1], set out the first principles for the integration of health, safety and ergonomics in the design and arrangement of the machinery spaces onboard ships. The circular's main objectives are (1) to improve safety of machinery spaces and (2) to ensure the effectiveness of their operation.

At a European level, a SURSHIP project called Engine Control Room - Human Factors (ECR - HF) [2] in which field studies onboard seven Swedish ships were carried out, ended in January 2009. This project concluded, inter alia, that in order to improve the efficiency of engine control room operations, their design should be addressed by recommendations and regulations from the maritime industry, including classification societies.

Moreover, Bureau Veritas while carrying out a study in 2008 on the ergonomic design of the means of access onboard commercial ships, identified machinery spaces as some of the most dangerous areas onboard merchant ships in terms of number of potential accidents. This is supported the Jensen et al. (2005) [3] and Hansen et al. (2002) [4]. studies that demonstrate that a significant number of accidents at sea (respectively around 20% and 30%) happen in the engine rooms. This can be explained on the one hand by the fact that machinery spaces are places where seafarers have to perform a large number of tasks and on the other hand because they are environments that group many industrial-specific and maritime-specific occupational hazards. These accidents seriously disrupt the smooth running of the ship and lead to additional costs.

For these reasons, classification societies, as technical depositaries, should provide the maritime industry with some practical standards for increasing the effectiveness of shipboard operations preventing the occurrence of occupational hazards in the machinery spaces.

Thus, Bureau Veritas has developed a novel approach based on Human Factors principles, risk analysis and accident investigations. In this approach, the ship is viewed with a holistic approach in which the hull (in the wider sense), the ship's equipment and the seafarers are constantly interacting. Consequently, in this approach, the design and arrangement of the machinery spaces are very closely correlated to the operation, maintenance, inspection and repair activities of seafarers, and other maritime professionals, as well as their physical and cognitive capacities.

The main objectives of our paper are: to present the approach that we developed and, show its application for the development of design requirements for the machinery spaces and their arrangement onboard merchant ships. An important aspect of the work we are carrying out is the integration of users' characteristics and requirements in the development of design standards for the machinery spaces. This integration is a key factor for the successful completion and validation of our research study. The study can be spilt up into five steps:

- Acquiring the pertinent data regarding the design of machinery spaces;
- Identifying and ranking the occupational hazards one can face in machinery spaces;
- Comparative studies between the planned procedures and the practical necessities faced by crew;
- Studying the activity of seafarers through the framework of human machine interaction for mitigating so-called "human errors" and;
- Deriving requirements and best practice for the design and arrangement of machinery spaces.

## THE MACHINERY SPACES

### Definition / Description

In this paper, the terms 'machinery spaces' and 'engine room' (not to be confused with 'engine control room') are assumed to have an equivalent meaning; they describe all rooms, spaces, areas onboard a ship and all equipments that are involved in providing the following main shipboard supply services: propulsion, steam for heating (fuel, etc.), water for cooling,

water for fire fighting, compressed air for warming up engine, compressed air for controls and services, electrical power for lighting and power supply for the numerous onboard equipments, heating and driving electric motors (thrusters, etc.), air conditioning, hot and cold water, sewage treatment, and several other services depending on the type of ship run.

In fact, machinery spaces can be described in several different ways. An example of formal descriptive framework could be composed of three or four complementary and overlapping approaches to each of which would correspond a model of the machinery spaces:

- A model by types of rooms: this physical description of the machinery spaces allow the analysis of their arrangements in terms of the location of each piece of equipment within a defined space or room that can correspond to different functions or different circuits.
- A model by type of flows or by circuits: there are onboard four main types of circuits with three distinct type of flows namely, the water circuit, the lubrication oil circuit, the fuel oil or fuel gas circuit and the air circuit. Each circuit contributes to providing several different services onboard.
- A model by equipments grouping the same types of equipments in same categories since they have the same general way of functioning and are operated and maintained in quite the same way. Pumps for instance can be found in many different places in the machinery spaces while they have quite the same function.
- A model by functions or type of services, grouping equipments that contribute to fulfilling the same goal which can be a service onboard such as “electricity for lighting” or the same function such as “providing compressed air for starting main engine”. This model allows a macroscopic view of the functioning of machinery and quick understanding of the impact of component, equipment and systems failures on the ship operation.

One could argue that only one model, particularly the most detailed one, would be enough in itself to be a basis for the analysis of the design and arrangement of the machinery spaces. However, we understand later in this paper that this is not so simple and that these different descriptions are of a significant value for addressing the most comprehensive number and wider spectrum of hazards in the machinery space (we define in the following sections that in this paper, that the term ‘hazard’ is used in its widest sense): different levels of description and even different view angles are necessary for extracting different aspects of the various areas we are addressing, especially for such complex systems as machinery spaces.

It is very time consuming (requires much resources and data), not possible, or simply it is not our goal to build generic descriptive models of machinery spaces in general. Thus we cannot pretend covering all aspects of their design and

arrangement. Moreover, there are always new equipments being developed and then installed onboard, always new technologies integrated in the engine room so that it would not be relevant to be too precise in the description: there are a great number of different ship types, and many different arrangements for the same kind of ships depending on the ways the vessel is intended to run, the area where she is intended to sail and the characteristics of the equipment chosen.

### **Tasks in the machinery spaces**

Now that the hardware part of the machinery spaces has been introduced in the previous section, it is of paramount important to introduce the human element part of them. Indeed, even with the highest level of automation the time when ships and particularly machinery spaces will not require any man intervention is not likely to come soon. Therefore, the way engine room systems work and interact cannot be reasonably described if excluding the description of the tasks to be carried out by seafarers: onboard commercial ships, there are still a very large number of different tasks to perform in the engine room that can be day to day routinely based, planned for maintenance, or occasional repairs. In fact, the machinery spaces are a 24/24 living system requiring much attention; this is the heart of the ship and any serious malfunction of its equipment can potentially lead to accidents such as collisions (due to steering problems, maneuverability problems for instance), groundings (due to loss of propulsion for instance), fire and explosions, etc.

The complexity of these numerous tasks to be carried out, their repetitiveness, the level of concentration they require, and many other factors influence seafarers’ behavior. In fact, even whether there are well-defined tasks attached to other well-defined procedures, themselves corresponding to some well-defined scenarios and situations, seafarers do not always act according to these prescribed tasks as initially expected. This is due to many reasons that mainly come from the way they assess the situations they face, (the way they build a representation of the world they are in), the way they interpret their explicit and implicit objectives and the procedures they have to use, adopt a personal strategy. This is often interpreted as complacency or rule violation but this should not be systematically seen as a bad thing. In any way people do not function, like machine do, so we cannot expect them to follow strictly instructions they are given if they think or feel that they are reasonably not appropriate to the situation they face. This is for crisis situations in which emergency actions have to be made quickly but also for more static situations for which seafarers tend to optimize in their way routine tasks they are assigned to carry out.

To summarize, the real activity is different from the prescribed task or prescribed work and therefore, both have to be described in order to understand the way machinery spaces are operated, identify the hazards and barriers to efficiency and safety and derive some advice and guidelines. Here again, we suggest using different tasks descriptions from three categories of situations. The tasks can be modeled using the following groups:

- Routine operations mainly consisting in watchkeeping, monitoring alarms in the engine control room, monitoring gauges and indicators, lubricating equipments, and inspections.
- Maintenance operations are organized according to the maintenance plan defining the number of running hours until such or such maintenance task of a defined equipment is required. They can be quite quick or time consuming particularly when the facilities are not convenient for moving parts and accessing equipment. Maintenance operations occur sometimes at sea or at berth or dry dock.
- Repair operations come after damage of equipment. They can be urgent in case of a critical damage at sea or even in bad weather conditions for instance and requiring quick diagnosis of the situation, quick decision-making and quick actions in order not to delay too much the voyage and/or engage safety of the vessel.

### Identification of hazards

Considering the environmental factors such as temperature, air quality, noise and vibrations, the numerous types of equipments and tasks that seafarers have to carry out in the machinery spaces of commercial ships, an unbelievable number of occupational hazards can be found there. They highly depend on the inherent nature of the equipment (rotating machinery, corrosive liquids) the size of the rooms and clearance around the equipment but as well on the way equipments and facilities are arranged one next to the other (concept of functional grouping). Here we are talking about hazards in the wide sense, not only potentially impacting directly safety and health of seafarers. However in this paper, we define some other types of hazards which are indirectly linked to occupational health and safety, namely hazards linked to decrease in the working performance. Indeed, non-intuitive arrangements and designs of the equipment, irrelevant or non-appropriate (regarding real situations in the field) tasks and procedures, stress producing factors such as repeated noise expositions, do cause seafarers' discomfort (notably due to working postures), do cause delays in the repair and maintenance operations, do complicate their work and are at the origin of absences (mind), fatigue and ultimately contribute to the so often quoted human errors. The mechanisms causing occupational accidents (accidents in general) are sometimes very complex and result from the combination of many factors or hazardous situations which are correlated each other. Therefore, in order to address a maximum number of hazards and be as comprehensive as possible in their identification, models are required: tools for manipulating things and concepts that are not so often systematically addressed in a holistic way.

This first section presented the authors' views on what the machinery spaces are and provided an informal general approach for the description and modeling of the arrangement, design, operation and hazards of and in machinery spaces.

Furthermore, it is necessary to build up a more formal framework, or a methodology for targeting hazards, analyzing designs and arrangements and developing recommendations.

## A METHODOLOGY FOR INCLUDING HUMAN FACTORS IN THE DESIGN OF MACHINERY SPACES

### The main concepts

#### *Why develop standard human factors based design requirements?*

The best way to increase operational efficiency and occupational safety through human factors is to carry out a full human factors engineering analysis during the design stage of a ship. However this means engaging some resources that ship owners may not be keen on supporting these days. In addition, design engineers are not used to emphasize seafarers' activity when designing ships because they were not taught or trained to do so; the objectives and even the terminologies of human factors and marine engineering seem a priori quite different. Therefore standard design and layout requirements that take into account ergonomics can be very useful and beneficial to design engineers who will be advised on how to better integrate the human element without carrying out a very detailed analysis. This means standards could lead to performance and safety increase at almost no costs for the owner. Bureau Veritas, as a classification society, is consequently developing ergonomics/human factors based guidelines for the design and layout of machinery spaces onboard merchant ships.

#### *A holistic/systemic approach*

Our approach is based on a holistic model of the ship. Firstly, the ship is considered as an entity constantly interacting with its environment: the sea, the weather conditions, other ships, ports, cargo, etc. Secondly, the entity 'ship' is composed of three systems which are constantly interacting in order to achieve a common goal: bring a cargo from location 'A' to location 'B' in a limited time and without any casualty. These three systems (or sub-systems) are the hull and superstructure, the equipment, and the human element i.e. seafarers.

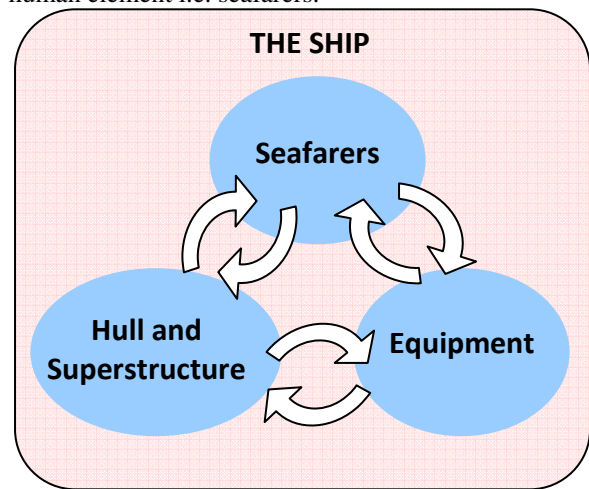


Figure 1: Systemic model of the ship

This model presented on figure 1 above is a global view of the ship and indeed, each of the three systems are themselves composed of many interacting subsystems. Therefore, a very complex system can be used to describe the ship at a more detailed level, when considering the different actors and the different tasks they have to carry out in relation to the numerous pieces of equipments.

### ***A risk-based methodology***

From the famous human drama of the sinking of the Titanic, to the environmental pollutions due to the sinking of the Erika, passing by the hijacking of the Sirius Star, the awareness of the entire society has been raised on the safety and environmental issues these last years. Now clearly not only the maritime industry's stakeholders are interested in managing risks emerging from cargo and passengers transportation. Furthermore, the costs associated to these accidents often imply 'repair' costs of millions dollars for the owners and for the society as well (trials, fines, value of the cargo, cleaning of pollution, etc.). Therefore, some significant effort is engaged in preventing and mitigating such catastrophic maritime accidents which appear reasonably unacceptable financially and in terms of societal risk.

However, if P&I clubs seem to record increases in claims recently, we could maybe try to find a part of the explanation somewhere else. In fact, by considering unacceptable the occurrence of major ship casualties, it seems that in terms of risk acceptance, implicitly, society tends to find it more tolerable to loose one life several times a years in many isolated accidents, than loosing the same number of lives during a unique catastrophic event, which somehow reasonably makes sense for almost all of us. But moreover, we can wonder in what extent and until which limit we can consider that loosing

In fact, we can think in the same way about environmental and financial costs and in these cases it is finally easier to make trade-offs between amounts of money or equivalent number of oil barrels than it is for lives.

Coming back to the design and arrangement of the machinery spaces, the methodology uses risk as a way to identify as rationally as possible the most critical operational and occupational hazards. Practically, it means that we use some risks indexes as the weighted association of a frequency index and a consequence or severity index. We remind the reader that potential consequences of the hazards identified are in terms of impact on seafarers' physical integrity but as well on their cognitive capacities and their performance in carrying out their duty.

### ***An ergonomics/human factors based methodology***

As explained in sections above, our holistic approach's relies on the fact that humans operating the ship are very legitimately at least as important as the hardware i.e. the hull, superstructure and the equipment. Therefore, we need a study framework and some tools dedicated to the description and analysis of people's activities in the machinery spaces, as well as tools and theories

for the development of recommendation for improving operational effectiveness and occupational health and safety in these areas. This framework is human factors or ergonomics: the study of human work and human at work. Many very different tools can derive from human factors since this science is at the cross road of many other sciences such as engineering, psychology, cognitive sciences, biomechanics, sociology, etc. Therefore, its fields of application can be:

- the work organization in terms of working hours, team working, allocation of resources,
- the design of work such as the design of the tasks to be carried out in terms of complexity, required skills, required competences and knowledge,
- workplace design, meaning the physical environment around the worker in terms of equipment, tools, air quality, temperature, controls, interfaces, etc.

Consequently, ergonomics can be used for the description and analysis of the tasks to be carried out in the machinery spaces, the real activities of seafarers, the development of recommendations for the design and layout of the equipment in the machinery spaces as well as the design of the numerous human-machine interfaces (control boards, screens, gauges, indicators, etc.).

### **The steps**

The methodology presented step by step in this section is based on the concepts of holistic approach, risk, and ergonomics/human factors defined on the previous section. These steps are basically run sequentially, one after the other, however, as shown on figure 3 hereafter, they are part of an iterative process. Indeed design processes based on human factors, in order to be used effectively, require a dynamic adjustment of the design recommendations to the inputs updates (as explained in the first step: data collection – user feedback).

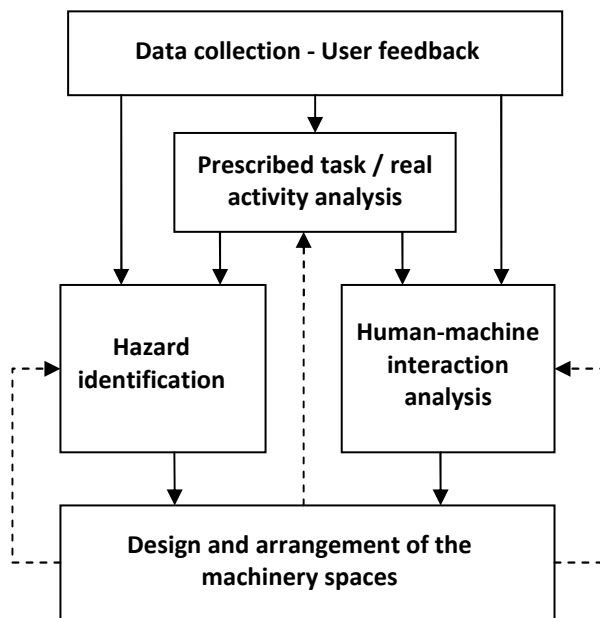


Figure 3: Methodology for integrating human factors in the design of machinery spaces onboard merchant ships

Each step is described in the most generic way as possible since this methodology, even if it is used here for improving efficiency and safety by the design of the machinery spaces, has already been used (in a slightly different version) for developing design guidelines ensuring a safe design of the means of access onboard commercial ships [5]. Obviously, since this methodology is derived from well known widespread principles and practice it can be also used for other areas onboard ships and offshore platforms or even other types of ‘facilities’ (onshore for instance).

### Data collection - user feedback

The first step is probably the most important one since it is used for feeding all other steps of the methodology: a significant amount of data is needed for the description and modeling of the machinery spaces, description and modeling of the routine, maintenance and repair operations and the associated tasks, description and modeling of operational and occupational hazards. It is important in this phase to gather accurate information on the equipment design and layout for different types of engines and ships, the corresponding procedures for normal operation, degraded functioning modes and emergency modes. Liaison with ship operators is encouraged for getting this kind of data. When it comes to the identification of hazards in the machinery spaces, investigation of accident through reports is very helpful as well as some statistical data from recent studies such as the 2004 and 2002 Danish and Norwegian studies one of which was submitted to the information of the International Maritime Organization (IMO) [6].

However, all these data sources reflect a certain reality which is not systematically the field reality. Moreover, the best way to know about the hazards faced by seafarers is to ask directly (or indirectly) their opinion about these hazards: the way they

assess them, their experience of accidents that happened to them or that they know have occurred to seafarers (many small accidents are not recorded in databases or their reports are not accessible to people external to the shipping company), near-misses which are rarely recorded because sometimes not even identified or taken seriously. From seafarers, one can also learn more on their feeling of when and why they think they experience loss of performance sometimes.

Furthermore, not only the identification of the operational and occupational issues can be elicited from seafarers, but also information of what is their real activity is compared to what the prescribed tasks they are assigned to carry out. In fact, as mentioned earlier in this paper, seafarers tend to adapt their way of working in line with a strategy they build more or less consciously in order to match the prescribed objectives as they personally interpret them from the recommendations and procedures they have got, and their personal objectives derived from the way they interpret their job and the way they assess the status of the machinery and their diagnosis of the equipments, and assumptions they make [7]. Understanding how and why they build these strategies through their feedback could reveal some relevant and different (sometimes better) ways to organize the work and the operations.

Finally, their feedback is crucial for developing design recommendations for the layout of the engine room since they are the final users: we cannot pretend deriving design improvements in terms of safety and operation from a unique initial identification of the hazards, the needs, the requirements; users have to be integrated somehow in the design process or here the process of developing design recommendations so that they can provide their opinion on the benefits/utility and the practical aspects. This way, design requirements can be adjusted iteratively in order to match seafarers’ needs and physical capabilities.

This concept of trying to match the workplace and the tasks to the needs, skills, knowledge and physical as well as cognitive capabilities of the users during the design phase is called ‘user centered design’ [8].

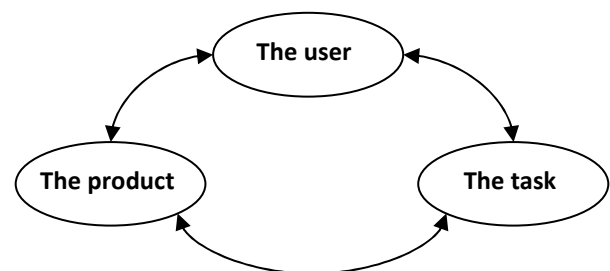


Figure 4: User-centred design (Pheasant & Haslegrave 1996)

In the section on the application of the methodology different types of user feedback are investigated.

### Prescribed task / real activity analysis

The concept of the seafarer as an actor of the ship operation is truly introduced in the second step when comparing their real activity when onboard in real situation to the prescribed tasks

and behaviors expected from them in such situations and trying to understand the underpinning mechanisms. Before comparing these prescribed tasks and real activities, it is important in this step to find a formal way of modeling them so that the comparison will be more structured and easier to carry out. Various widespread techniques for task analysis are available in the literature and are widely used [9] such as Critical incident technique, Hierarchical Tasks Analysis (HTA), Table-tip analysis, Barrier and work safety analysis or ergonomics checklists. The 'right' technique can be chosen regarding the objective of the analyst which can be :

- Task data collection methods
- Task description techniques
- Task simulation methods
- Task behavior assessment methods
- Task requirement evaluation methods

At the end of this second step, the machinery spaces are quite comprehensively modeled in terms of the environment, the equipment, and all the associated operational aspects.

### ***Hazard identification***

The third step consists in (a) identifying the largest number of operational and occupational hazards in the engine room and (b) ranking these hazards using a risk measure in order to assess their criticality and focus on those who first of all are intolerable for the ship owner or the ship manager, and then those which do not require much prevention and/or mitigation effort. Hazard identification should be partially based on user feedback as explained earlier; however, the identification phase should be as comprehensive as possible in order to be proactive and try to anticipate or foresee hazards that have not caused operational performance losses or occupational accidents. Then comes the modeling phase: this allows the description of very different hazards on the basis of the same framework. Once these hazards have been identified, it is important to find the best way to assess their likelihood of occurrence and their potential impacts on seafarers' performance and safety through extrapolations, expert judgment and user feedback.

### ***Human-machine interactions analysis***

This step is mainly fed by the analysis of the real activity of seafarers in the machinery spaces. In fact, various requirements for many pieces of equipment can be derived from the analysis of the interactions between the seafarers and the machinery. We can analyze what these interactions are, what they could be, what they should be in order to be more efficient in the operation of the engine room. To this extent, we use a framework that is composed of three complementary approaches corresponding to three levels of interaction between seafarers and the machinery:

- The human machine interface approach raises the question: What are the functionalities available to the user through the interface? Criteria for designing a quality interface can be the self-learning capacity, the

quality of displays and commands, the adaptability to individual differences, the protection against user errors and transparency. Typical interfaces between human and machinery spaces are controls, screens, panel boards, visual and sound alarms, gauges and indicators. This is the lower level approach that is often unfortunately confused with the whole concept of 'human machine interactions'.

- The human machine system approach raises the questions: How does the machine help me to complete the user's objectives? In other words, how does the machine and user cooperate in order to achieve the user's goal? For assessing the HMI, we use some ergonomic criteria such as those defined by Bastien and Scapin for the design of interactive software programs [10]. This approach is the middle level approach and leads to requirements deriving from the articulation of different tasks sequentially or in parallel instead of only one.
- The third approach raises the question: How does the machine change the user's activity? This approach considers the activity of the user and the tasks he has to perform in order to carry out his duty at work. It is the macroscopic and higher level approach. It will lead to some functional requirements for the different devices and pieces of equipment of the engine room. The idea is to analyze in what extent the modification of the design and arrangements influence the operations and activities of seafarers and therefore the machinery's operational performance.

Basically, each approach will determine – through some human factors criteria – a type of functional requirements or directly design requirements that will then lead to the development of recommendations or guidelines.

### ***An iterative design process***

We conclude this section presenting the methodology dedicated to the development of design recommendations for the machinery spaces of commercial ships by describing the final step. We are trying to understand what would be the more useful design and arrangements requirements in terms of format and content for helping design engineers to integrate easily human factors in their work for a limited cost for the owner.

The basic principles for the requirement are derived from the classification Rules, the SOLAS convention and other IMO regulations, feedbacks from seafarers, industry's best practice documents and the work done for the engine control room in the ECR-HF Swedish project [ref]. Then, workplace design analysis (using anthropometry) is used for setting some dimensional standards. All the previous steps are inputs for this final one in which all recommendations from existing regulations, all advice and solution proposals from seafarers' feedbacks, all requirements from the analysis of human machine interactions are aggregated to derive recommendations providing at least the same levels of efficiency and safety as those of the existing regulations.

Requirements should be derived here using principles and criteria from human factors or ergonomics such as the so-called four cardinal constraints of ergonomics as mentioned in Pheasant & Haslegrave 2006 [8]:

- ease of use,
- comfort,
- functional efficiency and,
- quality of working life

Depending on the type of design requirements aimed at, different types of ergonomic analyses can be carried out. Some techniques focus on the cognitive aspects of the tasks and will therefore provide advice on how to reduce (or sometime increase in case ‘annoying’ routine tasks) the cognitive workload of seafarers by the design of the machinery; some other will focus on taking into account the physical capabilities of seafarers in order to derive requirements ensuring safe, comfortable and effective working postures or a minimum clearance around some parts of the equipment to facilitate access for such or such operations.

## CONCLUSION

Bureau Veritas is aiming to publish a guidance note providing the recommendations and best practice for the design and layout of the engine room as they will be derived from the research study based on the principles and methodology presented in this paper. This work is intended on the one hand to raise the awareness of the maritime industry on the importance of using human factors in the ship design process or more generally considering seafarers’ future activity in the machinery spaces before the final design stage, and on the other hand to provide ship design engineers with practical and simple tools for integrating human factors when designing the engine room.

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