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Remarks on human reliability with reference to marine power plant operation

Analiza niezawodności człowieka w kontekście pracy w siłowniach okrętowych

Leszek Chybowski, Zbigniew Matuszak

Akademia Morska w Szczecinie, Wydział Mechaniczny, Instytut Technicznej Eksploatacji Siłowni Okrętowych, 70-500 Szczecin, ul. Wały Chrobrego 1-2, e-mail: l.chybowski@am.szczecin.pl, zbimat@am.szczecin.pl

Key words: human factor, human error, human reliability measure, marine system, offshore technical object

Abstract
This article is an introduction to the analysis of human reliability in specific anthropotechnic systems, such as marine power plants. The human factor is discussed as one that is responsible for creating dangerous situations during the operation of offshore technical objects, mainly sea-going vessels. Besides, we indicate the place of a human being in marine technical systems, his specific qualities and interaction with the environment. Selected classifications of human errors are given as well as their particular causes. Then we present a model of an autonomous system referring to the human being, based on Mazur's concept. Besides, potential fault nodes resulting from that model are specified. We show examples of quality and quantity models that are helpful in an analysis of the reliability of the human, an element of such technical systems as marine power plants. Final remarks include possible applications of mathematical models herein presented in analyses as well as some restrictions in the use of these models. Emphasis has been put on essential difficulties in utilizing simulators for the examination of the reliability of the human considered as the operator of a marine power plant. These difficulties are due to a variety of interactions within the system (the vessel) and relations with the external environment.

Słowa kluczowe: czynnik ludzki, błąd człowieka, miara niezawodności człowieka, system okrętowy, obiekt oceanotechniczny

Abstrakt
W materiale dokonano ogólnego wprowadzenia do tematyki analizy niezawodności człowieka w specyficznych systemach antropotechnicznych, jakimi są siłownie okrętowe. Wskazano na udział czynnika ludzkiego w powstawaniu sytuacji niebezpiecznych podczas pracy obiektów oceanotechnicznych, w tym statków morskich oraz miejsce człowieka w okrętowych systemach technicznych, jego specyficzne cechy i interakcje z otoczeniem. W artykule przedstawiono wybrane klasyfikacje błędów człowieka oraz wskazano szczególne przyczyny ich powstawania. Przybliżono, oparty na koncepcji Mazura, model systemu autonomicznego w odniesieniu do człowieka oraz wyszczególniono wynikające z tego modelu potencjalne węzły niezdatności. W artykule pokazano przykładowe modele jakościowe i ilościowe pozwalające na wsparcie analizy niezawodności człowieka jako elementu systemów technicznych, jakimi są siłownie okrętowe. W uwagach końcowych omówiono możliwość wykorzystania w analizach przedstawionych w pracy modeli matematycznych i ewentualne ograniczenia ich zastosowań oraz zaakcentowano istotne trudności wykorzystania symulatorów w analizie niezawodności człowieka – eksploatatora siłowni okrętowej z uwagi na specyficzne interakcje zarówno wewnątrz systemu jakim jest statek, jak też związki ze środowiskiem zewnętrznym.

Introduction

Practice shows that the human factor makes up the greatest hazard that may cause a widely understood reduction in the quality of operation of most systems, e.g. biological, economic, social, technical (including marine objects) and others. Disturbances in the operation of systems caused by people (omission, ignorance, fatigue etc.) are dealt with as various facets of system analysis. They mainly pose a threat to occupational safety and operational reliability, and lead to a reduction of the effectiveness of anthropotechnical systems operation. This also refers to marine transportation systems and their sub-structures, such as vessels and offshore technical objects and port systems. With reference to sea-going vessels, one of the essential factors ensuring safe and reliable execution of tasks assigned to them is the proper functioning of marine power plants in cargo and/or passenger ships as well as special-purpose vessels. Further in this article we examine some problems, which include selected quantity and quality measures connected with the determination of power plant operator's reliability. The material presented herein refers to the problem of unintended human unreliability. This restricts the application of presented models so that they cannot be used in intentional actions of a person aimed at deliberate steps putting a system in a down state, e.g. industrial sabotage.

Place of a human in the evaluation of marine power plant operation

The marine power plant is an anthropotechnical system of the *human – technical object – environment* (*H-T-E*) type. An example of basic interactions within such a system is shown in figure 1. The safety of the marine power plant and its operation can be analyzed by evaluating elements of a given system, consisting of a human – *operator* and the *environment* (*H-T-E* system). By decomposing the element *H* (*human*) we can distinguish the direct user (operator) and various classes of operational managers (management level). In the area *E* (*environment*) we can identify a person not directly associated with object operation and an artificial environment (co-operating objects and others, occurring only in the environment) and the natural environment (inanimate: atmosphere, lithosphere, hydrosphere and animate: fauna and flora).

The human, an element of the *H-T-E* system, may generally be considered in various ways: a user handling a machine (pilot, driver, etc.), a technician servicing a machine in the maintenance process (state control, running or preventive repairs), a system element realizing certain particular functions (investigator, observer), a person using a service provided by a machine (e.g. a passenger of a given means of transport) [1]. If we consider marine power plants, various aspects of activities

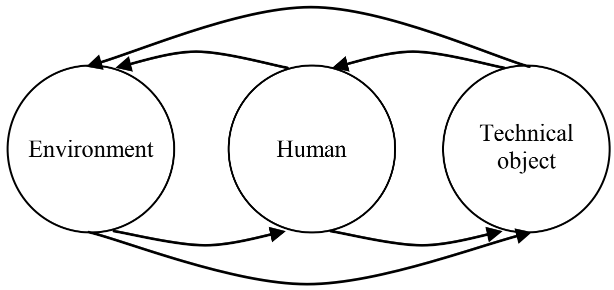

Fig. 1. The model of the human – technical object – environment system
Rys. 1. Model systemu współzależności człowiek – objekt techniczny – środowisko

of the personnel interacting with machinery and equipment should be taken into account. Apart from major overhauls executed with the help of land-based personnel, in normal operating conditions many functions are performed by ship's engineers, which is due to unusual working conditions and no assistance from land-based infrastructure. In this approach, the ship's engineer (locally on the operational and management levels) is both the user of marine power plant subsystems (use and technical state control), a person executing a number of maintenance processes (repairs, maintenance, inspection of spares and writing orders for spare parts and operating materials), at the same time being the system observer who prepares reports and improves his professional competence (particular functions).

It should be noted that the marine power plant system has some untypical features, such as the impossibility to postpone some maintenance works, no possibility for spares to be delivered promptly, necessity of implementing temporary solutions in emergency situations that on land would be out of consideration, and a strong influence of external environmental factors (waves, tides, winds, storms etc). In addition, ship's personnel is under strong stress that may occur over a long period of time (isolation from the society for a long time) and suddenly happening in emergency situations, when a quick response may be critical in rescuing human life or preventing injuries. The environment can also affect the object indirectly, changing the condition of *human-operator*. The reverse effect is also possible. All the above properties make the statistical share of humans in marine accidents quite high. The most frequent cause of marine accidents are errors made by the human (ship's personnel) while operating the ship (handling and maintenance), and any other object at sea.

According to a local analysis of marine accidents [2] that occurred in 2002, covering 834

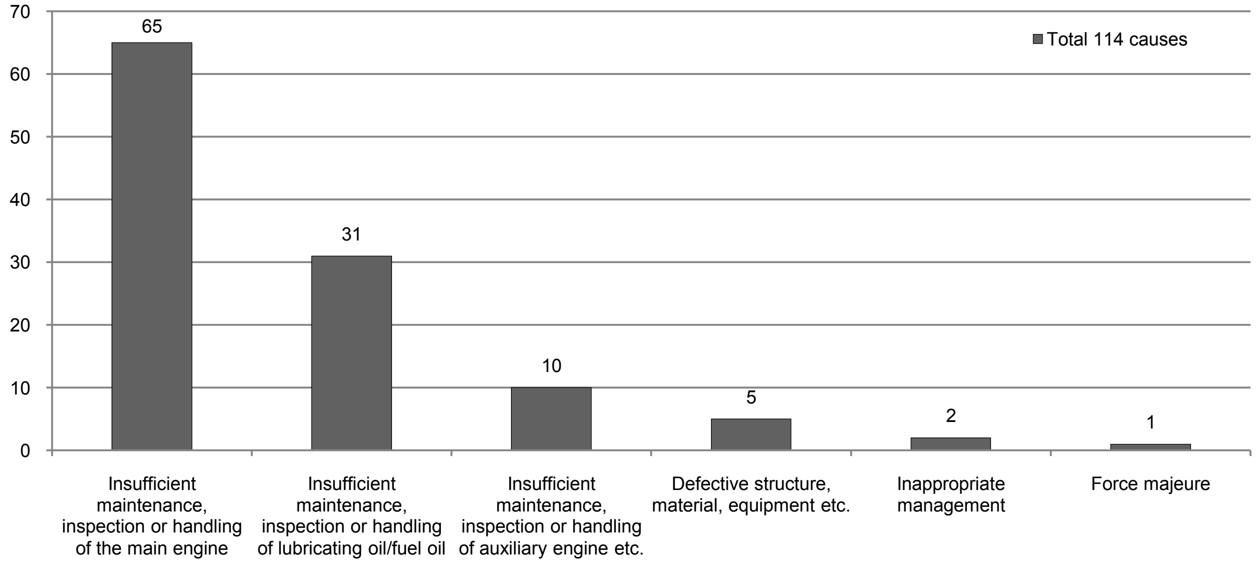

Fig. 2. Causes of marine accidents in 2002 connected with a failure of ther marine power plant; report of the Marine Accident Inquiry Agency
Rys. 2. Przyczyny wypadków morskich w 2002 r. związane z awarią siłowni okrętowych; raport Agencji Badania Wypadków Morskich

accidents involving 1259 ships, about 99 cases (12% of all accidents) are accidents due to a failure of marine machinery. The shares of particular causes of failures of ship's installations for this case are shown in figure 2. The greatest share, i.e. 65 failures are connected with improper maintenance, inspection or handling of main engines. Errors in the operation of power plant systems and auxiliary engines are also focused on the human (operator), being an element of the marine power plant system.

Generally, the unreliability of humans (personnel) who work surrounded by the marine environment is one of the main causes of accidents, failures and sinking of offshore systems. Most often such accidents directly or indirectly cause the pollution of the marine environment or loss of human life. That unreliability most often results from improper adjustment of the objects as such or their components to the needs and possibilities of the human. Considering the man as an operator of a machine – a technical device – we see it is important that action controlling that machine are taken in due time and correct (error-free). That is because both system effectiveness and, in many cases, the safety of operator, other persons and technical system components or the environment depend on it. Promptness and correctness are basic characteristics of the human as an element of the *H-T-E* system [3]. Safety should characterize the entire system: a person affects the system safety to same degree as work in improper time, inaccuracy and human erroneous actions generate emergency situations. Kotarbiński extended the classification of human errors that can be considered in the presented approach of *H-T-E* interactions in nine different categories of errors [4]: substitutes of actions (actions directed at an object very similar to the proper object), automatic implementations (propagation of actions in the wrong direction), losing (squandering of objects), lateness (including sluggishness and laziness), unsuccessful searching (goal not achieved despite the effort made), failing to interfere (passive attitude in taking actions), impulsive (feverish) reactions and practical errors based on logical errors (execution of wrong conclusions).

Event rankings in marine power plant systems

During the quality analysis of technical system reliability, including such systems as offshore technical objects, usually minimal cuts of unreliability are searched for on the basis of the system model (block diagram of reliability, fault tree, binary equation etc.). When a set of all minimal cuts is found, it is possible to further process the data in order to identify the type of individual elements (events) in the obtained minimal cuts. On this basis we can also infer the priority of a given cut. The criticality rank [5] of a given cut may then be adopted from the following ranking (see fig. 3) of component events corresponding to the elements of the system presented.

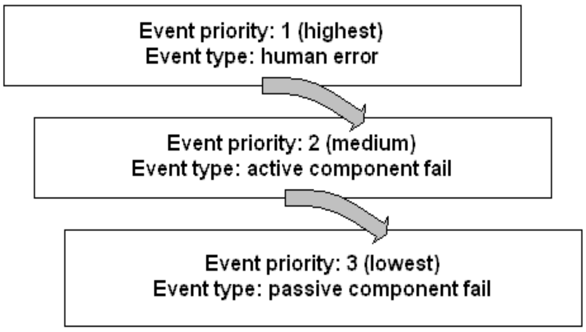

Fig. 3. Ranking of primary events used in the qualitative reliability analysis
Rys. 3. Klasyfikacja zdarzeń podstawowych wykorzystywanych w jakościowej analizie niezawodności

The ranking of events presented in figure 3 is based on an assumption that human errors occur more frequently than active components failures, and the latter are more frequent than passive component failures. For example, a pump in operation is much more susceptible to failures than a standby pump. The ranking above may be used for the quality classification of the priorities of minimal cutsets composed of two or more primary events. Figure 4 presents ranks of two-component minimal cutsets.

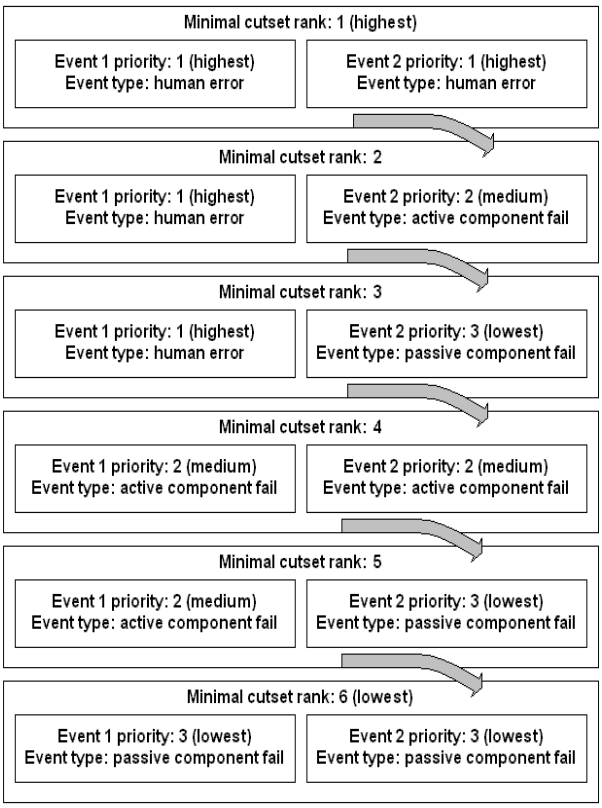

Fig. 4. Ranks of minimal cutsets composed of two primary events
Rys. 4. Klasyfikacja czynników wpływających na podstawowe zdarzenia

Human reliability in the technical system

Human reliability is considered as person's ability to perform certain actions in a preset time interval and in specified conditions of the environment. Among various functional states of the human two main groups are identified: normative and pathological states. It is usually difficult to find a clear-cut distinction between the two states, although this distinction is important while we consider reliability and intend to determine the effect of these states on human errors. In the assessment of operator performance what is important is the effect of his actions as well as the manner in which the effect has been achieved, if it is important due to processes taking place in control objects and due to the economy of their operation process.

A model of operator's (ship's engineer's) reliability independent of time corresponds to routine work done in the process of using marine installations (plants), such as switching on and off machines and equipment, switching over machines and installations, changing operating parameters and settings of automatic control systems. This model has the following form:

$$R = P(Z = 1, W = 1) \tag{1}$$

where:

- Z – discrete random variable such that: $Z = 1$, when an operator's task has been realized, and 0 – when it has not been realized;
- W – discrete random variable such that: $W = 1$, when the task has been performed in a correct manner, and 0 – when it has been executed in an incorrect manner.

A model of time-dependent reliability is useful in assessing ship's engineer's (operator's) performance in emergency situations or such situations in which failing to perform the task in a specified time poses a threat to a installation or objects located in its environment. Certain cases can be distinguished in which the engineer, responding to disturbances or failures carries out routine actions and such that are taken solely on the basis of his knowledge. Time-dependent reliability is described by the relation (2). The time of execution is generally subject to the log-normal distribution [6].

$$R(t) = P(Z = 1, T < t) \tag{2}$$

where:

- T – continuous random variable expressing the time of task execution by the operator;
- t – positive real number.

The human being is a highly complex system with a redundant reliability structure. From the cybernetic point of view the human can be regarded as an autonomous system because he:

- has a capability of self-control,
- is capable of preventing the loss of that ability,
- is able to maintain a functional balance in spite of changes in his environment,
- tries to keep up his existence and functions for his own interests.

The human body fulfils all functions of an autonomous system, which allows to classify, according to Mazur's concept [7], various human qualities, such as: affecting the environment (through *effectors*), acquiring information from the environment (through *receptors*), taking energy from the environment (through *alimentators*), storing and processing information (using *correlators*), processing and storing energy (using *accumulators*), maintaining the functional balance (using *homeostats*). A simplified representation of the human as an autonomous system and relations *Human-Environment* are shown in figure 5.

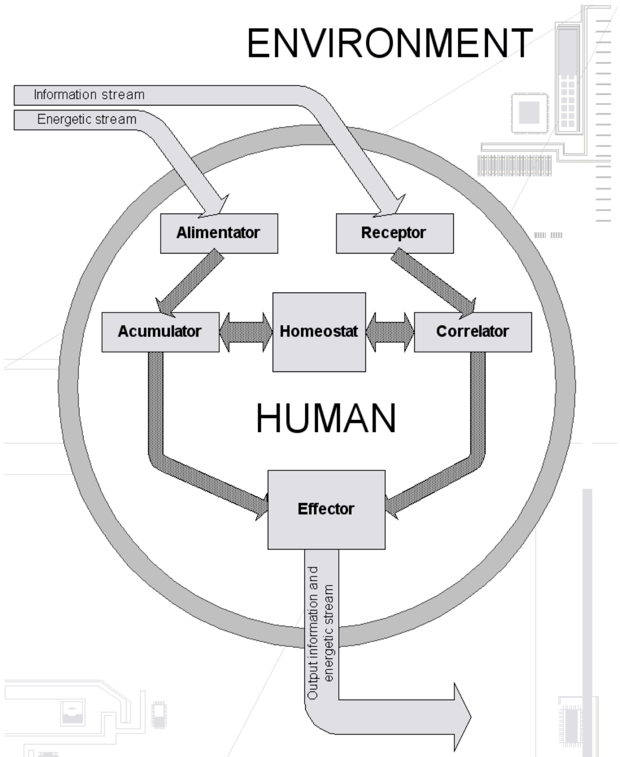

Fig. 5. Structure of the human as an autonomous system
Rys. 5. Człowiek jako przykład systemu autonomicznego

From the point of view of reliability the human can be characterized by a number of errors. Some classifications have already been presented. Using the model shown in figure 3, we can classify human errors by taking into consideration incorrect functioning of specific elements of the system modelled in this way. The following errors can be distinguished in particular: errors of reception of information from the environment (these may result from the imperfection of *receptors* and from disturbances in information acquired from the environment), errors of information processing (these may be due to excessive amount of information exceeding the capabilities of the *correlator* or its being unadjusted to process a particular piece of information), incorrect influence on the environment (these errors may be due to the decrease of functional stability or exceeding of the capabilities of *effectors*), lost or restricted ability to act due to injuries of human organs, lost or restricted ability to adapt to changes occurring in the environment. Taking into consideration the above mentioned characteristics we can evaluate such qualities of human reliability as faultlessness and effectiveness. These two characteristics determine *human operational reliability*, while failure-free operation determines *biological reliability*.

As the problems of research into human errors and their consequences in *H-T-E* systems are highly complex, there is a need to develop new relevant methods of investigation. According to Brandowski, operator's reliability can be determined through simulator-based examination [8]. This is connected with the fact that in natural conditions the data indispensable for the estimation of operator's reliability characteristics cannot be obtained, as tasks performed by the operator in dangerous situations may cause loss of property and pose a threat to human life and health.

The quantitative measure of human biological reliability can be expressed as the probability of maintaining the ability to act in a specified time interval and in specified conditions. With reference to the human being we can utilize the engineering concept of *element failure*, and thus use such notions as reversible failures (temporary instantaneous loss of ability to act as a result of stress, illness, alcoholic stupor) or irreversible failures (improper functioning of certain organs of the human, death).

Human reliability can be measured as the probability of success achieved in performing a job or task at a given stage of system functioning within a specified time interval, determined by task execution time requirements. A correct action consists in undertaking planned activities in scheduled time. An incorrect action can damage a device or may change the course of performing actions (task). Jaźwiński [3] presents a model of time required for task execution by a person.

The human needs a specific time T_1 to receive information (depending on capabilities of the *receptors*), information analysis time T_2 (depending on the capabilities of the *correlat*), decision-making time T_3 (co-operation between the *correlator and the effector*), decision execution time T_4 (dependent on the capabilities of the *effector*). A task will be done in due time / promptly, if the specified time for task execution will satisfy this inequality

$$T_1 + T_2 + T_3 + T_4 \le T_0 \tag{3}$$

where:

T_0 – preset time for task execution.

Lomov proposed four principal quantitative indexes of human reliability, namely the correctness, availability, restitution and validity indexes [9].

Operator's correctness index P_j is a measure defining the probability that the operator will work without making any errors (probability of error-free, / correct / task execution), which can be expressed in this form:

$$P_j = \frac{N_j - n_j}{N_j} \tag{4}$$

where:

N_j – total number of performed operations,
n_j – number of errors made.

Operator's availability index K is the probability that the operator will be able to start work any any moment, such that:

$$K = 1 - \frac{T_1}{T} \tag{5}$$

where:

T_1 – time when the operator withdraws from work; it is a period of operator's absence from his work station,
T – total time of operator's work.

Restitution index P_{pop} is connected with operator's self-control and correcting his own actions. This index determines the probability of correcting errors made by the operator, such that:

$$P_{pop} = P_k \cdot P_w \cdot P_p \tag{6}$$

where:

P_k – probability that a controlling device will send a signal,
P_w – probability that the operator will detect the signal sent by the controlling device,
P_p – probability that incorrect operations will be corrected when done for the second time.

Validity index P_a (operator's working time adequacy) is expressed by the probability of performing the tasks by the operator in time $\tau < T_0$, written in this form:

$$P_a = P(\tau < T_0) = \int_0^{T_0} f(\tau)\,\mathrm{d}\tau \tag{7}$$

where:

$f(\tau)$ – function of density of the probability that the operator will execute the task.

When the operator works continuously, the probability $R_0(t)$ of his correct (error-free) work is sometimes described by analogy to technical systems in the following form:

$$R_0(t) = \exp\left[-\int_0^t \lambda_0(\tau)\,\mathrm{d}\tau\right] \tag{8}$$

where:

$\lambda_0(t)$ – intensity of making errors by a person at an instant t.

The application of this approach, however, is very difficult due to the fact that the human characteristics change affected by varying internal and external conditions. All this makes it at times impossible to describe clearly the relationship between operator's reliability and duration of his work.

Human ability to correct his errors can be regarded as the probability $R_{kb}(t)$ that an error admissible during task performance will be corrected after the time t at a specified workload and a state of environment is adequate to the task being executed. The probability of correcting an error is defined by this relation

$$R_{kb}(t) = \exp\left[-\int_0^t \mu(\tau)\,\mathrm{d}\tau\right] \tag{9}$$

where:

$\mu(t)$ – frequency of correcting an error by a person at an instant t.

Operational reliability of the user-operator can be defined as the probability of correct and prompt task execution composed of elementary actions, and is described by this relation:

$$R_0 = \left(\prod_{i=1}^{N} P_i\right) \cdot P\left(\sum_{i=1}^{N} T_i \le T_0\right) \tag{10}$$

where:

P_i – probability of error-free (correct) execution of i-th action,
T_i – execution time of i–th action,
T_0 – time assigned to task execution.

When a ship's personnel acts under stress, e.g. while eliminating the consequences of a serious marine disaster in order to save their lives, magnitudes $T_i(i = 1,2,...,N)$ are stochastically dependent, that is probabilities P_i are functions of stress. Then practical use of the relation (10) becomes very difficult or just impossible. In order to determine human operational reliability computations using the presented mathematical models are supported by computer-aided simulations.

Final conclusion

During the realization of elementary actions (information reception and processing, decision making and execution) the operator may make errors. In this approach human errors can be traced at all the stages of the existence of a given technical system, including the marine power plant. In particular, these errors are as follows: designing errors due to insufficient designing quality, errors occurring due to improper performance of predicted maintenance activities by the personnel or due to the performance of unpredictable procedures, manufacturing errors caused by bad quality of work or improper material or by making a product not in accordance with the requirements, errors of technical maintenance occurring in the process of operation as a result of bad quality of repairs and assembly, errors of quality inspection resulting in acceptance of defective products as good ones, or acceptance of an overhauled machine with incorrectly repaired parts, errors of improper storage and transport.

Among errors made during personnel's work the following can be mentioned: insufficient qualifications of maintenance personnel, performing improper maintenance or handling actions, improper working conditions, insufficient or improper working tools, improper incentives for error-free work.

In spite of a wide range of mechanisms and locations where human errors are made, the fact that these processes are complex [10] and have a random character makes an analysis of the anthropotechnic system reliability very difficult. As a rule, in a reliability analysis of a specific system failures caused by the operator's error are omitted if they are nor very expensive to remove. In some particular situations they are even hidden.

Vessel crews are in a special situation, relying only on their skills, spares and supplies available on board and restricted possibilities of repairs in on board workshops. Furthermore, a crew, a small group of people staying together in a relatively restricted area for several months has specific mental, physiological, sociological and other conditions. All these factors lead to a conclusion that vessel personnel should be in the care of *personality psychologists*.

The combination of all relevant studies facilitates an analysis of social interactions in a group and mechanisms affecting the functioning of this group. Shipowners tend to economize at all costs, especially by reducing the number of on board personnel. This shows that shipowners have, unfortunately, a technocratic approach to operators of offshore technical systems.

Determining the reliability of a human as a technical system we should take into consideration a number of factors, such as: probability of an error that can be made while performing each operation within human activity; possibility of predicting most essential errors that can be made in the process of handling and maintenance of devices; frequency of failures of devices and technical systems caused by the human; taking into considerations those human errors that are irreversible; probability of correct operation of a device (system) providing an error has been made.

The selected measures of human reliability herein presented can be used in reference to marine power plants as a helpful tool in a preliminary assessment of how various types of events (human errors) affect and interact with failures of machines and devices.

The specific design of marine systems (many elements occur in many system cutsets) [11, 12] as redundancies in such systems are necessary /in connection with redundancies in such systems) as well as shortage of data obtained from operations of similar objects, i.e. vessels (due to the character of marine power plants, which are usually unique systems) may substantially hamper quantitative analyzes of human participation in putting a system in a down state.

Another essential factor which makes such analysis difficult is the character of works done during the operations of marine power plants that are never the same on various ships (even sister vessels); besides many works done even on the same ship are unique actions (performed just once during the overall maintenance process). In spite of the fact that simulators for identifying human reliability are a powerful tool in examining pilots (aeronautics, astronautics), these features of activities / work in the marine power plant significantly restrict possibilities of using such simulators in examining the reliability of a human – an operator of a marine power plant (ship's engineer). However, for certain activities / operations it is possible to adopt some analogous models from aeronautics, supported by data on pilots' reliability obtained from simulation tests.

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Recenzent:
dr hab. inż. Andrzej Grządziela
profesor Akademii Marynarki Wojennej w Gdyni