A model of occurrence of the situations endangering inland waterways passenger ships and the environment

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ABSTRACT

In this paper a four-state semi-Markov model of occurrence of the situations endangering inland waterways passenger ships, is presented. The model was elaborated in the form of the semi - Markov process, values of which are kinds of the states interpreted as the following situations : normal, complicated, hazardous and emergency. An example of realization of the process of changing the situations possible to occur during trips of inland waterways passenger ships, is presented. Also, formulae are attached, which make it possible to determine probabilities of occurrence of the mentioned situations during ship trips. The formulae were interpreted as safety measures of operation of inland waterways ship. Possibility of performing statistical investigations which could provide data for determining the mentioned probabilities was also stated.

Keywords : inland waterways ships, prediction of failure probability, availability indices of ship devices

INTRODUCTION

During voyage of inland navigation ships and also during their stopovers in river ports, can happen various situations which, from the point of view of degree of their seriousness, can be divided into [6, 9, 12, 14] : normal, complicated, hazardous, emergency and disastrous.

Direct users of such ships (e.g. officers, engineers) as well as indirect ones (e.g. ship owner) tend ensuring the normal situation, i.e. that in which safe operation of the ship is possible. The safe operation of inland navigation ship is such an operation which does not cause a hazard to the ship and the environment. Such hazard can happen in the case of occurrence of an extensive failure (breakdown) of any of such its devices which influences significantly assurance of required safety (e.g. propulsion system, steering gear, sewage treatment plant etc). Failures of such devices can lead to loss of health (and also life) of a number of passengers and crew members as well as pollution of the environment.

Consideration of features of inland navigation passenger ships – from safety point of view – as well as psychical and physical predispositions of their crews, and also operation and maintenance conditions of their devices, makes it possible :

- to precisely describe a kind of situation in which a given ship operates
- to assess expected value of duration time of particular situations in which every device ensuring safe operation of a given ship, can be found
- to determine frequency of occurrence of the mentioned situations during a longer time of performing shipping tasks by a given ship.

As the situations in which inland navigation passenger ship can find itself, are random events and their duration time is a random variable, one can apply the theory of stochastic processes [3, 6, 8, 10, 11] (after some simplifications) for determining occurrence probabilities of the event of finding such ship in the particular situations.

Hence investigation of safety of the considered ships and their operational safety during their tourist trips requires to build a stochastic model of changes of the mentioned situations in which the ships can be found. Such model is necessary for determining probabilities of occurrence of particular situations during a longer time interval (theoretically when $t \to \infty$).

To prevent occurrence of unwanted situations (different from normal one) is possible in the case of taking appropriate decisions first of all by direct (and sometimes also indirect) users of ships of the kind. In order to take such decisions, is necessary not only to know values of occurrence probabilities of the mentioned situations, but also values of probabilities of finding the crucial devices of the ships (e.g. their propulsion systems or steering gears etc) in the particular technical states such as : full serviceability, partial serviceability, task unserviceability, full unserviceability [6, 7, 8, 14]. Below, the problem is considered of determination of probabilities of occurrence of the above mentioned situations, namely :

s_0^* – normal, s_1^* – complicated, s_2^* – hazardous, as well as s_3^* – – emergency one.

FORMULATION AND SOLUTION OF THE PROBLEM

Changes of particular situations in which traffic of inland navigation ships can be realized, in contrast to sea-going ones, may be considered in the form of the random process $\{Y(t): t \geq 0\}$, discrete within the states and continuous with time, of the four-element set of states $S^* = \{s_j^*; i = 0, 1,..., 3\}$, where t – realization time of the process, which practically represents trip duration time of a given inland navigation passenger ship [4, 5, 14].

In this case general interpretation of the states $s_j^* \in S^*$ (j = 0, 1,..., 3) is as follows :

- s_0^* – normal situation
- s_1^* – complicated situation
- s_2^* – hazardous situation
- s_3^* – emergency situation.

The disastrous situation s_4^* which is considered in the case of sea-going ships, can be omitted when considering safety of inland navigation passenger ships. As sinkage of such ship is rather impossible because of very shallow waters in which such ship operates, as well as in view of ambient conditions which are much more mild than those at sea. However it can ground on a shoal and become an obstacle for navigation.

The distinguished states $s_j^* \in S^*$ (j = 0, 1,..., 3) occur at random instants and last within the time intervals $[\tau_0, \tau_1)$, $[\tau_1, \tau_2)$,..., $[\tau_n, \tau_{n+1})$, which are random variables.

In the normal situation (s_0^*) crews of inland navigation passenger ships (called further shortly :"ships") fulfil their duties in the conditions to which they are accustomed. Such conditions do not involve any excessive stress to the crews and do not push them to develop excessive physical and intellectual efforts.

The complicated situation (s_1^*) occurs when events making realization of a given task difficult, happen. In the case of passenger ships, among such events the following can be numbered a.o.: a failure of one of the main propulsion systems or all of them, i.e. a failure of the entire propulsion system of the ship. In such cases the ship crews are pushed to develop a short-term physical and intellectual effort to cope with tasks resulting from the necessity of removing causes of the occurred situation.

The hazardous situation (s_2^*) occurs when events making realization of a given task impossible, happen, for instance ship's arrival in time at a port, in line with expectations of tourists. Among such events the following can be numbered for instance: a failure of one of the main propulsion systems (or all of them) during worsening weather conditions (strengthening wind, or rainfall, increasing water depth and stream-way velocity of the river on which the ship sails), as well as a failure of steering gear, main electric switch board, underwater part of ship's hull, that leads to flooding its interior etc. In such cases to increase efforts of ship's crew to make the ship capable of safe sailing, is necessary.

The emergency situation (s_3^*) occurs when ship's crew cannot restore the technical state after occurrence of the mentioned failures, especially those of propulsion system and/or steering gear in conditions of worsening weather, strengthening wind etc, that makes anchoring the ship in the place of failure occurrence, necessary. Such state may endanger health and even life of the crew and perhaps also of some passengers especially those aged or having health problems.

In its initial phase, operation of every ship is usually realized in the normal situation determined by the following factors [1, 6, 7, 15] :

- the state of full serviceability of the object, especially of its propulsion system, steering gear and electric energy system
- the high level of psychical and physical predispositions of ship's crew members
- favourable ambient conditions in which the ship operates
- correct maintenance performed in advance, before commencing realization of a given task by the ship.

In the case of worsening the first of the three above mentioned factors and /or not performing the required maintenance (preventive or after-failure one) the ship (and also the considered process $\{Y(t): t \geq 0)$ undergoes transition from the state s_0^* to the state s_1^*, which is equivalent to the change of the normal situation (s_0^*) in which the ship has been operated in given waters, into the complicated one (s_1^*) whose interpretation was highlighted in [14]. The change occurs with the probability p_{01}, after the time interval which is realization of the random variable T_{01}, representing the duration time of the situation (state) s_0^* provided the next state will be the situation s_1^*. An appropriate action of the crew can certainly restore the situation s_0^* that may occur with the probability p_{10}, after the time interval which is realization of the random variable T_{10}. In the case of worsening the mentioned factors it may happen that to come back to the situation (state) s_0^* is not possible, that inevitably leads to the hazardous situation (state) s_2^*. It is equivalent to the transition of the investigated process $\{Y(t): t \geq 0\}$ from the state s_1^* to the state s_2^*. Such change of the situation occurs with the probability p_{12}, after the time interval being the realization of the random variable T_{12}.

Crew's actions appropriate to the situation may lead back to the situation s_0^*, however only after recovery of the situation s_1^*. Otherwise the situation s_3 (emergency) may appear due to worsening the technical state of the ship and its operational conditions, with the probability p_{23} and after the time interval being the realization of the random variable T_{23} which represents duration time of the situation s_2^* provided that the next will be the state s_3^*. From this situation it is possible sometimes to come back to the above mentioned situations, only as a result of crew's actions, but often it requires calling for help from the side of various rescue institutions.

Hence it can be stated that reasonable is to consider the process $\{Y(t): t \geq 0\}$ of the graph of changes of the states : $s_j^* \in S^*j = 0, 1,..., 3)$, presented in Fig.1.

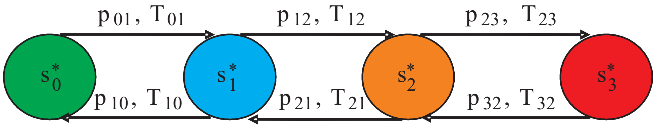

***Fig. 1.** Graph of state changes of the process {Y(t): t ≥ 0} .*

The above presented graph of changes of the states of the process $\{Y(t): t \geq 0\}$ is crucial for the proposed solution of the problem of determining probabilities of being the process in specified states, as it makes it possible to build the functional matrix necessary for determining the expressions for assessment of the mentioned probabilities. In the case of assuming another graph than that presented in Fig.1. other expressions for determining the probabilities will be obtained.

From the considerations it results that the appearance of the states $s_j^* \in S^*$ (j = 0, 1, 2, 3) depends on technical state of the main devices of ship especially its propulsion system, as well as on its ambient conditions of operation on a given waterway. Hence it is necessary to determine the set of technical states of the mentioned devices, knowledge of which could make it possible to avoid the most hazardous situations (and even emergency one) for the considered ships and the environment. The same conclusion concerns the set of technical states of the ships in question and their devices, which can appear during their tourist and recreation trips.

From the considerations presented in [5, 6, 10, 14, 15] it results that for determining the set of such states, is reasonable to assume the capability of fulfilling their tasks by the mentioned ships and their devices, to be the classification criterion of the states. In line with the criterion the following classes of the technical states (called further simply : states) can be distinguished :

- the full serviceability state s_1, which makes it possible to use ships and their devices in every conditions and load range, to which they have been adjusted during their designing and manufacturing
- the partial serviceability state s_2, which makes it possible to use ships and their devices in limited conditions and load range, lower than those to which they have been adjusted during their designing and manufacturing
- the serviceability state s_3, which does not make it possible to use ships and their devices in accordance with their mission

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(because of their failed devices, e.g. propulsion system, performing of maintenance operation of the devices, during which ship operation is not possible, etc).

The specified states $s_i \in S$ (i = 1, 2, 3) of particular devices of the ships in question can be recognized by relevant diagnostic systems (SD) whose applicability depends on quality of the diagnosing system (SDG) as well as its capability of recognizing the mentioned states of the devices of every ship, considered as the diagnosed systems (SDN) [3, 6, 7].

An example of realization of the process $\{Y(t): t \geq 0\}$ is presented in Fig.2.

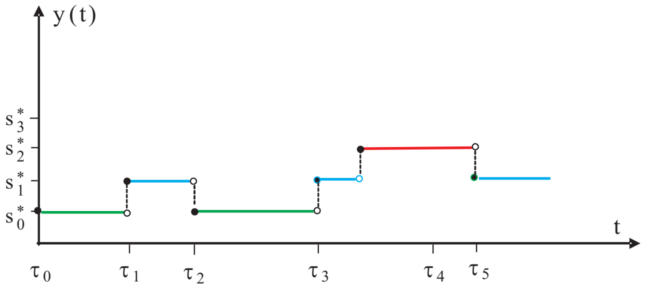

***Fig. 2.** An example of one-dimensional run of the process {Y(t): t ≥ 0} .*

Changes of the states belonging to the set $S^* = \{s_i^*; i = 0, 1,...,3\}$, during operation of every ship in question, can be considered as the process $\{Y(t): t \geq 0\}$ whose realizations are constant (uniform)within particular time intervals and continuous on the right [6, 11, 14]. Lengths of the intervals are the random variables T_{ij} equivalent to duration time of the state $s_i^* \in S^*$ of the process in question provided that the next is the state $s_j^* \in S^*$, where : i , j = 0, 1,..., 4, and $i \neq j$. The variables are random, independent, having the finite expected values $E(T_{ij})$ and positively concentrated distributions. Moreover the process is characterized by that the duration time of the state s_i^*, occurred in the instant τ_n , as well as the state appeared in the instant τ_{n+1} do not depend stochastically on the previous states and their duration time intervals. Hence it can be assumed that future states (situations) depend first of all on the current situation. It means that the process $\{Y(t): t \geq 0\}$ can be considered as a semi-Markov process of the graph of state changes, presented in Fig. 1. In order to define the process its initial distribution P_i as well as its functional matrix **Q(t)** should be determined in advance.

The initial distribution of the process $\{Y(t): t \geq 0\}$ is as follows :

$$P_i = P\{Y(0) = s_i^*\} = \begin{cases} 1 & \text{for} \quad i = 0 \\ 0 & \text{for} \quad i = 1, 2, \ldots, 3 \end{cases} \tag{1}$$

In accordance with the graph presented in Fig.1 the functional matrix is of the following form :

$$\mathbf{Q(t)} = \begin{bmatrix} 0 & Q_{01}(t) & 0 & 0 \\ Q_{10}(t) & 0 & Q_{12}(t) & 0 \\ 0 & Q_{21}(t) & 0 & Q_{23}(t) \\ 0 & 0 & Q_{32}(t) & 0 \end{bmatrix} \tag{2}$$

The elements of the matrix (2) are non-decreasing functions of the variable t, which represent the probabilities of transition of the process $\{Y(t): t \geq 0\}$ from the state s_i^* to the state s_j^* ($s_i^*, s_j^* \in S$; i , j = 0, 1,..., 3; $i \neq j$) during the time not greater than t, and which are described as follows [6, 11] :

$$Q_{ij}(t) = P\{Y(\tau_{n+1}) = s_j^* \\ \tau_{n+1} - \tau_n < t \,|\, Y(\tau_n) = s_i^*\} = p_{ij}F_{ij}(t) \tag{3}$$

where :

$s_i^*, s_j^* \in S(i , j = 0, 1,..., 3; i \neq j)$, and :

p_{ij} – probability of one-step transition in uniform Markov chain inserted in the process $\{Y(t): t \geq 0\}$,

$F_{ij}(t)$ – cumulative distribution function of the random variable T_{ij} representing duration time of the state s_i^* of the process$\{Y(t): t \geq 0\}$ provided that the next is the state s_j.

The probability p_{ij} is interpreted as follows :

$$p_{ij} = P\{Y(\tau_{n+1}) = s_j^* \,|\, Y(\tau_n) = s_i^*\} = \lim_{t \to \infty} Q_{ij}(t) \tag{4}$$

In the situation, solving the so formulated problem consists in finding the limiting distribution of the process $\{Y(t): t \geq 0\}$, which has the following interpretation :

$$P_j = \lim_{t \to \infty} P\{Y(t) = s_j^*\} \quad ; \quad j = \overline{0{,}3}$$

The distribution can be determined by using the formula [11, 14] :

$$P_j = \frac{\pi_j E(T_j)}{\sum_{k=0}^{3} \pi_k E(T_k)} \quad ; \quad j = 0,\ 1,\ \ldots,\ 3 \tag{5}$$

where :

$$\pi_j = \lim_{n \to \infty} \frac{1}{n} \sum_{k=1}^{n} P\{Y(\tau_n) = s_j \,|\, Y(0) = s_i\}, \text{ and :}$$

$[\pi_j; j = 0, 1,..., 3]$ is the stationary distribution of the Markov chain $\{Y(\tau_n): n \in N\}$ inserted in the process $\{Y(t): t \geq 0\}$.

The distribution satisfies the set of equations (6) and (7) [11, 14] :

$$\sum_{i=0}^{3} \pi_i p_{ij} = \pi_j \quad ; \quad i, j = 0, 1, \ldots, 3 \tag{6}$$

$$\sum_{i=0}^{3} \pi_i = 1 \tag{7}$$

The matrix (2) is stochastic, hence the matrix of the transition probabilities $\mathbf{P} = [p_{ij}]$, i , j = 0, 1,..., 3 is as follows :

$$\mathbf{P} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ p_{10} & 0 & p_{12} & 0 \\ 0 & p_{21} & 0 & p_{23} \\ 0 & 0 & p_{32} & 0 \end{bmatrix} \tag{8}$$

Therefore the equations (6) and (7) which characterize the limiting distribution π_j , j = 1, 2, 3 of the Markov chain $\{Y(\pi_n: n = 0, 1, 2,...\}$ inserted in the process $\{Y(t): t \geq 0\}$ can be presented in the form of the set of equations [14] :

$$\left.\begin{aligned} [\pi_0, \pi_1, \pi_2, \pi_3] \begin{bmatrix} 0 & 1 & 0 & 0 \\ p_{10} & 0 & p_{12} & 0 \\ 0 & p_{21} & 0 & p_{23} \\ 0 & 0 & p_{32} & 0 \end{bmatrix} &= [\pi_0, \pi_1, \pi_2, \pi_3] \\ \pi_0 + \pi_1 + \pi_2 + \pi_3 &= 1 \end{aligned}\right\} \tag{9}$$

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By solving the set of equations (9) the following relationships are obtained according to the equation (5) :

$$P_0 = \frac{p_{10}p_{21}p_{32}E(T_0)}{M} \quad ; \quad P_1 = \frac{p_{21}p_{32}E(T_1)}{M}$$
$$P_2 = \frac{p_{12}p_{32}E(T_2)}{M} \quad ; \quad P_3 = \frac{p_{12}p_{23}E(T_3)}{M} \qquad (10)$$

and :

$$M = p_{10}p_{21}p_{32}E(T_0) + p_{21}p_{32}E(T_1) + $$
$$+ p_{12}p_{32}E(T_2) + p_{12}p_{23}E(T_3)$$

where :

p_{ij} – transition probability of the process $\{Y(t): t \geq 0\}$ from the state s_i^* to the state s_j^* ($s_i^*, s_j^* \in S$; i, j = 0, 1,..., 3; $i \neq j$)

$E(T_j)$ – expected value of the random variable T_j(j = 0, 1,..., 3) representing duration time of the state $s_j^* \in S$(j = 0, 1,..., 3) of the process $\{Y(t): t \geq 0\}$ regardless of the state to which the process comes.

The expected values $E(T_j)$ depend on the expected values $E(T_{ij})$ as well as on the probabilities p_{ij}, in the following way :

$$E(T_j) = E(T_i) = \sum_j p_{ij}E(T_{ij}) \quad ; \quad i, j = \overline{0,3} \quad ; \quad i \neq j \qquad (11)$$

The particular probabilities P_j(j = 0, 1,..., 3) have the following interpretation :

$$P_0 = \lim_{t\to\infty} P\{Y(t) = s_0^*\}$$
$$P_1 = \lim_{t\to\infty} P\{Y(t) = s_1^*\}$$
$$P_2 = \lim_{t\to\infty} P\{Y(t) = s_2^*\}$$
$$P_3 = \lim_{t\to\infty} P\{Y(t) = s_3^*\}$$

The probability P_0 can be considered to be a measure of safe trip of inland navigation ship including safe operation of its propulsion system, as well as any other energy system or device installed on the ship, hence also a measure of safety of passengers and crew members.

Also the probability P_1 can be considered as a measure of safe trip and safe operation of any energy system as well. Whereas the remaining probabilities (P_2 and P_3) can be taken as measures of unsafe trip of the ship in question, hence of unsafe operation of propulsion system of the ship and also any other energy system or device. The probabilities contain information on possible appearing a hazard and its growing beginning from the situation s_2^*, hazardous one. Hence the probability $P_B = P_0 + P_1$ can be taken as the safety measure of operation of inland navigation passenger ship and any device installed on it, on whose functioning safety of the ship and persons onboard, depends.

In order to obtain approximate values of the probabilities P_j(j = 0, 1,..., 3) to assess p_{ij} and $E(T_j)$ is necessary.

The assessment of the probabilities p_{ij} and expected values $E(T_j)$ is possible after obtaining the realization y(t) of the process $\{Y(t): t \geq 0\}$ within appropriately long time intervals of investigations, i.e. for $t \in [0, t_b]$, and $t_b >> 0$. Then can be determined the numbers n_{ij}(i,j = 0, 1,..,3; $i \neq j$), which represent numbers of transitions from the state s_i to the state s_j within appropriately long time.

The following statistic appears to be the largest likelihood estimator of the transition probability p_{ij} [11] :

$$\hat{P}_{ij} = \frac{N_{ij}}{\sum_j N_{ij}} \quad ; \quad i \neq j \quad ; \quad i, j = 0,\ 1,\ \dots,\ 3 \qquad (12)$$

whose value : $\hat{p}_{ij} = \dfrac{n_{ij}}{\sum_j n_{ij}}$

constitutes the assessment of the unknown probability p_{ij} of transition of the process $\{Y(t): t \geq 0\}$ from the state s_i to the state s_j.

From the mentioned run y(t) also the realizations $t_j^{(m)}$, m = 1, 2,..., n_{ij} of the random variables T_j can be obtained. By applying the discrete approximation the estimation $E(T_j)$ in the form of the mean arithmetic value of the realizations $t_j^{(m)}$ can be easily obtained [2, 13, 15].

COMMENTS AND CONCLUSIONS

Operational safety of inland navigation passenger ship, hence also its propulsion systems and other energy systems, depends on many factors. Among the most important the following can be numbered :

- ☆ technical state of propulsion system devices and other ship power plant equipment
- ☆ reliability and a degree of adjustment of diagnosing systems to recognizing crucial states of ship power plant devices
- ☆ ambient conditions during ship's voyage
- ☆ qualifications of ship's crew and its psychical and physical resistance to effects of destructive factors which may happen during ship's voyage
- ☆ availability (in particular readiness) of water, land and medical rescue units.

To maintain a satisfactory (required) operational safety level of energy systems, especially propulsion ones, of inland navigation passenger ships, hence the ships themselves, during the phase of their operation, is not possible without knowing a.o. :

- ❍ occurrence probabilities of the situations $s_j^* \in S^*$ (j = 0, 1,..., 3), especially those hazardous to ships in operation, i.e. s_2^* and s_3^*
- ❍ occurrence probabilities of the states $s_i \in S$ (i = 1, 2, 3), first of all the states s_2 and s_3, i.e. those limiting possible loads onto the ship devices, especially those installed in ship power plant, to which they have been adjusted during their designing and manufacturing
- ❍ indices of readiness of ship's devices
- ❍ probabilities determining likelihood of diagnosis on the state of particular ship devices.

Applicability of the mentioned to determining a decision situation as regards ship operational safety, can be showed with the use of the statistical theory of operational decision-taking. To this end it is necessary to know likelihood of diagnosis on the technical state of devices of the considered ships, especially their energy and propulsion systems, steering gears and other ones significantly influencing safety of shipping on inland waterways.

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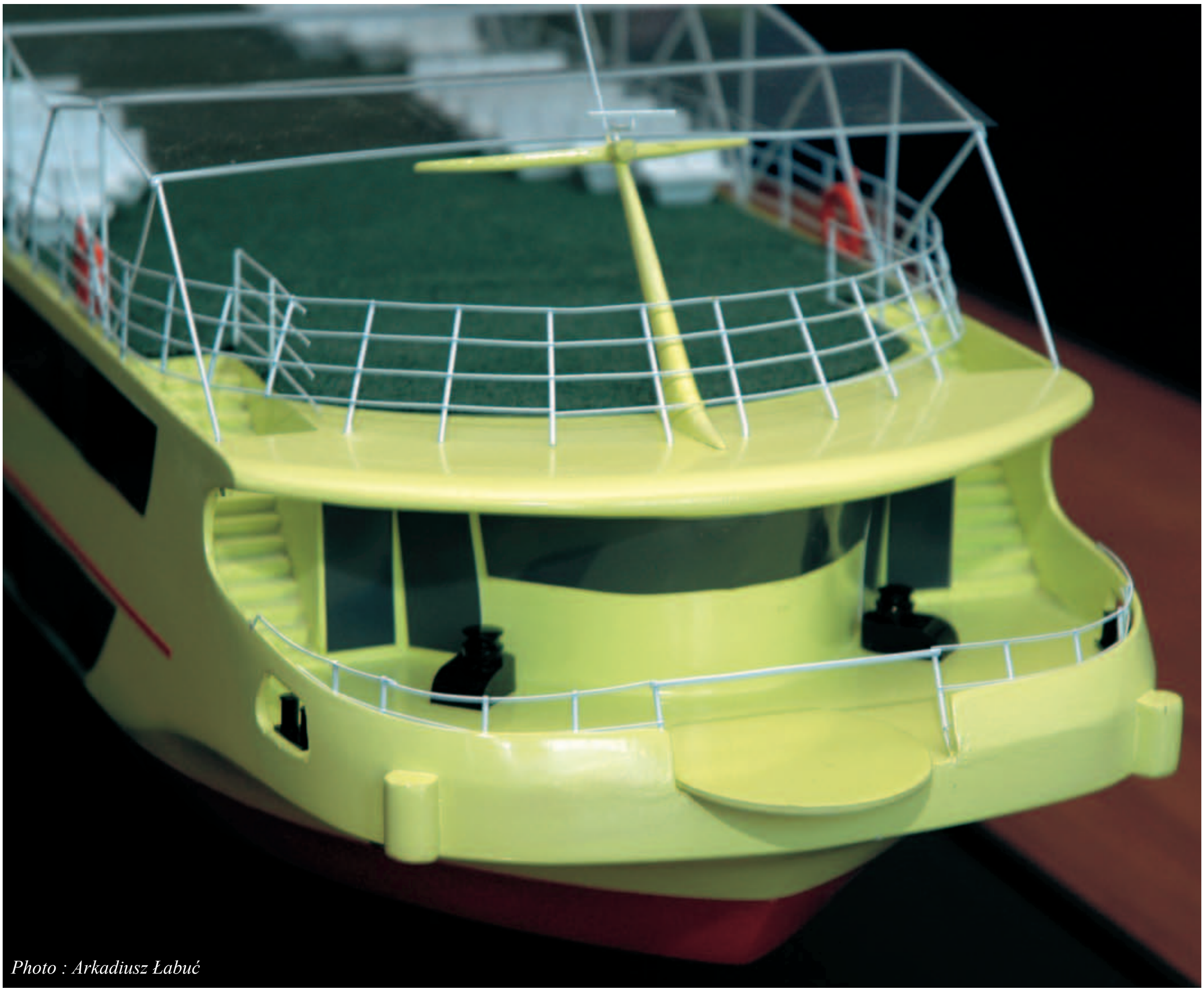

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