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# Functional model of river-sea ships operating in European system of transport corridors

## Part I.
## Methods used to elaborate functional models of river-sea ships operating in European system of transport corridors

**Magdalena Kaup**, Ph. D.
Szczecin University of Technology

ABSTRACT

*This paper presents a functional model of river-sea ships (shortly called: SRM) operating in European system of transport corridors. It is composed of two parts: Part I contains a descriptive model of functioning the SRM fleet with taking into account various shipping tasks as well as impact factors (external and internal factors, limitations and criteria). Also, a mathematical model of functioning the SRM fleet, including choice of relevant economic criteria (e.g. profit maximization, capital return period minimization etc), is presented. Results achieved on the basis of the functional model are presented in Part II of the paper.*

**Keywords**: European system of transport, river-sea ships, river-sea transport system, water transport

## INTRODUCTION

If current linear and point infrastructure of water transport over a given area and database of geography of cargo flows are at disposal, one can select such way of transport, out of those available, which will satisfy requirements of both cargo-providers and cargo-recipients at an accepted level of values of technical, economical, functional and environmental criteria. However various strategies of cargo shipping and loading should be considered. In order to select a concrete shipping strategy to be applied to river-sea transport system it is necessary to elaborate in advance a model of functioning the SRM fleet, that means:

- elaboration of possible schemes of the functioning of river-sea ships
- determination of permissible zone of operation of river-sea ships
- adjusting the selected shipping strategy to shipping route
- elaboration of a mathematical model for assessing the functioning of river-sea ships according to different scenarios
- elaboration of technical design assumptions for river-sea ships.

## SHIPPING TASKS AND FUNCTIONING SCHEMES OF RIVER-SEA SHIPS

The functioning of river-sea ships has been always and still is subordinated to concrete shipping tasks, i.e. transport of a given amount of cargo over a given route within a given period. On them is dependent the functioning scheme and kind of assumed shipping strategies. Form of river-sea shipping tasks in European system of water transport corridors depends on:

- rate of cargo flows
- direction of cargo flows
- geography of inland waterways and sea routes
- traffic capacity of inland waterways
- functional parameters and location of ports.

Essence of a given shipping task depends on:

- length of shipping route
- number and traffic capacity of sea and inland ports, locks etc, planned to be used
- permissible speed of transport units on a given waterway,
- kind and amount of cargo shipment within a planned cargo flow
- traffic limitations on inland waterways, e.g. seasonal ones.

The following transport strategies should be taken into account for river-sea shipping:

- shuttle mode – consists in shipping between two terminal ports
- linear mode– consists in regular shipping between selected ports in compliance with a given schedule
- delivery (tender) mode – consists in shipping between two ports where one of them can be used as an intermediate port
- block – shipment mode – consists in shipping between two terminal ports which may be different depending on instantaneous demand on shipping services.

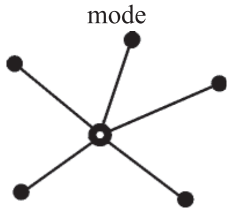
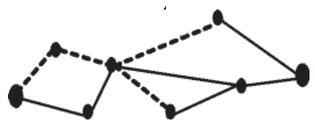
Among the strategies dependent on shipping task other types can be also distinguished. Some of them are given in Tab. 2. Characteristic features of the basic shipping strategies are presented in Tab. 1.

*Tab. 1. Shipping strategies in river-sea transport*

| No. | Strategy type | Advantages | Disadvantages |
|---|---|---|---|
| 1. | Shuttle mode | ▪ short transport time,<br>▪ regularity of connections<br>▪ certainty of shipping orders/ tasks | ▪ necessity of having permanent cargo flows<br>▪ problems in ensuring full cargo load |
| 2. | Linear mode | ▪ regularity of connections<br>▪ possible application to long distance routes<br>▪ possible tending small shipments, | ▪ relatively long duration time of transport resulting from using intermediate ports |
| 3. | Delivery (tender) mode | ▪ short transport time<br>▪ relatively high usage effectiveness<br>▪ possible supplementing the shipped cargo mass | ▪ necessity of having additional shipping orders/tasks<br>▪ problems with ensuring full cargo load for ship<br>▪ a shipping coordination system is required |
| 4. | Block-shipment mode | ▪ easy to use<br>▪ not requiring permanent cargo flows<br>▪ possible application to routes in a broad range of length. | ▪ lack of regularity of connections<br>▪ necessity of shipping coordination. |

Source: The author's concept

*Tab. 2. Adjustment of permissible shipping strategies to shipping tasks in river-sea transport system*

| No. | Shipping tasks | Permissible shipping strategy |
|---|---|---|
| **1.** | Direct cargo shipping mode  (DCS group) | ▪ shuttle mode<br>▪ direct linear mode |
| **2.** | Cargo shipping in accordance with delivery mode  (CSDS group) | ▪ intermediate linear mode<br>▪ delivery mode (along supply sections)<br>▪ block - shipment mode (along supply sections) |
| **3.** | Cargo shipping in accordance with shipment consolidation mode  (CSSCS group) | ▪ „hub and arms" mode<br>▪ consolidation and decomposition mode |
| **4.** | Cargo shipping in accordance with multi-variant mode of  (CSMSR group) | ▪ linear mode with reserve connections<br>▪ Y-shuttle mode |

Source: The author's concept

Assessment of the functional effectiveness of river-sea ships as to shipping tasks can be performed by adjusting the shipping strategies as well as functioning schemes to a given shipping task.

When the types of shipping tasks and strategies presented in Tab. 1, 2 and 3, are taken into account a set of possible solution variants of the functional model of river-sea ships can be formed. Each of them should be decomposed in order to obtain one preferable functioning scheme of river-sea ships which contains detail information resulting from a considered shipping task. For every permissible connection of ports through a water transport corridor it is possible to perform calculations on the basis of which optimum functioning strategies of river-sea ships as well as design assumptions for them can be determined.

From the information contained in Tab. 2 it results that different shipping tasks can be aggregated into 4 basic groups which correspond with 9 permissible strategies.

To each of the groups concrete shipping strategies can be attributed. This can be illustrated e.g. by CSDS group to which, by making use of the intermediate linear strategy, the shipping task given in the Scheme 2 of Tab. 3, corresponds, and in the case of DCS group and the shuttle strategy - the task given in Scheme 1 of Tab. 3.

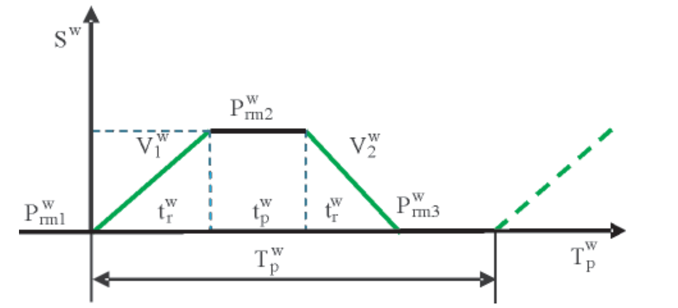
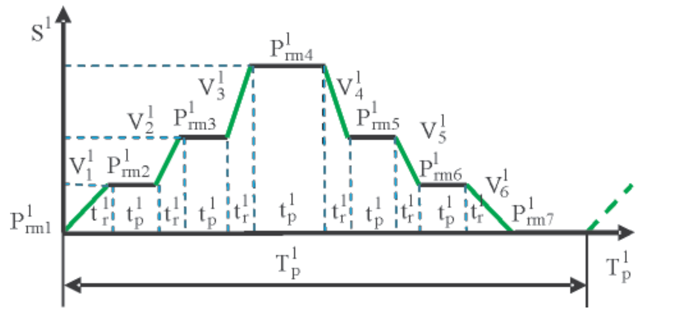
## FACTORS WHICH FORM FUNCTIONAL MODEL OF THE FLEET OF RIVER-SEA SHIPS

The functional effectiveness of river-sea ships in European system of transport corridors in accordance with concrete shipping tasks depends – directly or indirectly- on many external and internal factors (Fig. 1). The factors, depending on a considered navigation zone and characteristics of cargo flows over a given area, contribute - in a positively (e.g. low shipping rates, social acceptance) or negatively (e.g. ship speed limitation, low class of waterways, low traffic capacity of ports and locks) to the effectiveness of fulfilling the shipping tasks.

Apart from the forming factors, also technological and finacial limitations etc influence the functional effectiveness of river-sea ships. Therefore, is of a great importance to appropriately choose criteria (Fig. 2) according to which it will be possible to select the most effective system of functioning the SRM fleet in line with features of serviced cargo flows.

Models of functioning the river-sea ships in European system of water transport corridors greatly depend on changes in the external and internal factors. These constitute premises for building a multi-variant functional model of ships of the kind in question.

*Tab. 3. Selected examples of functional schemes of river-sea ship accomplishing concrete shipping tasks*

| No. | Shipping strategy | Functioning scheme in accordance with a given shipping task |
|---|---|---|
| 1. | ▪ shuttle mode |  **Scheme 1** |
| 2. | ▪ intermediate linear mode |  **Scheme 2** |

Source: The author's concept

where:

$T_p$ – cargoload shipping period of river-sea ship [days]

$S$ – assumed length of shipping route [km]

$t_r$ – voyage period [days]

$t_p$ – port lying period [days]

$V$ – permissible service speed [km/h]

$P_{rm}$ – particular river-sea ports.

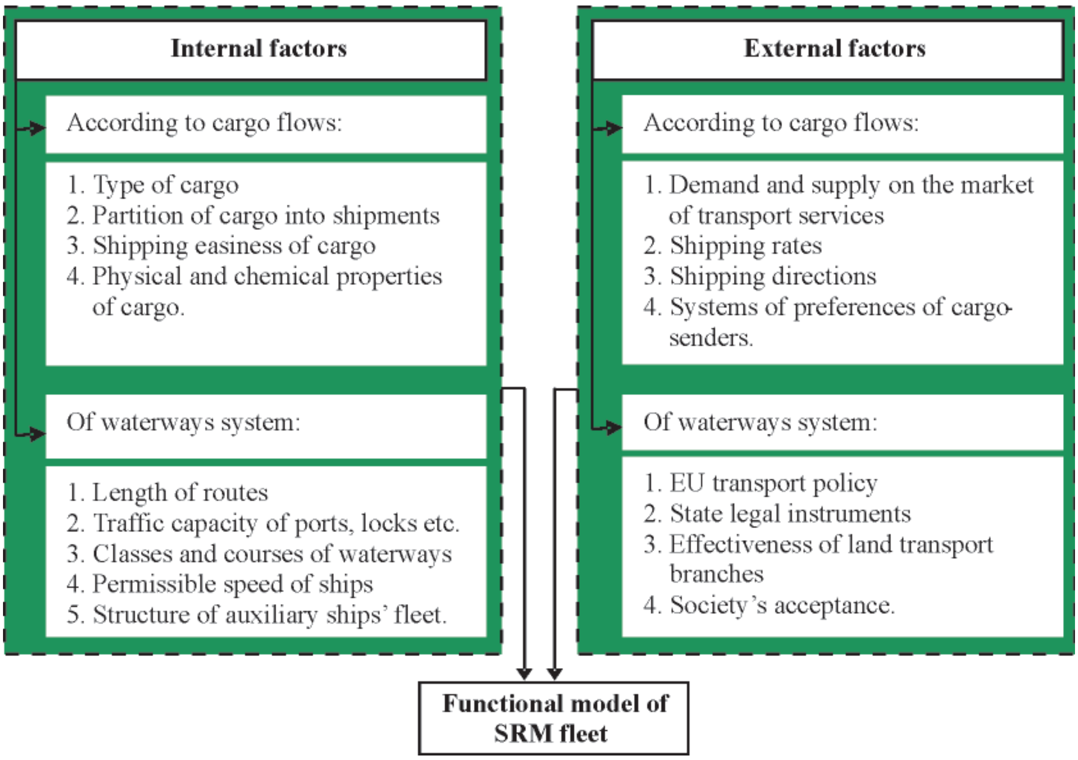



***Fig. 1.** Factors taken into account in assessing the SRM fleet shipping effectiveness.*
***Source**: The author's concept*

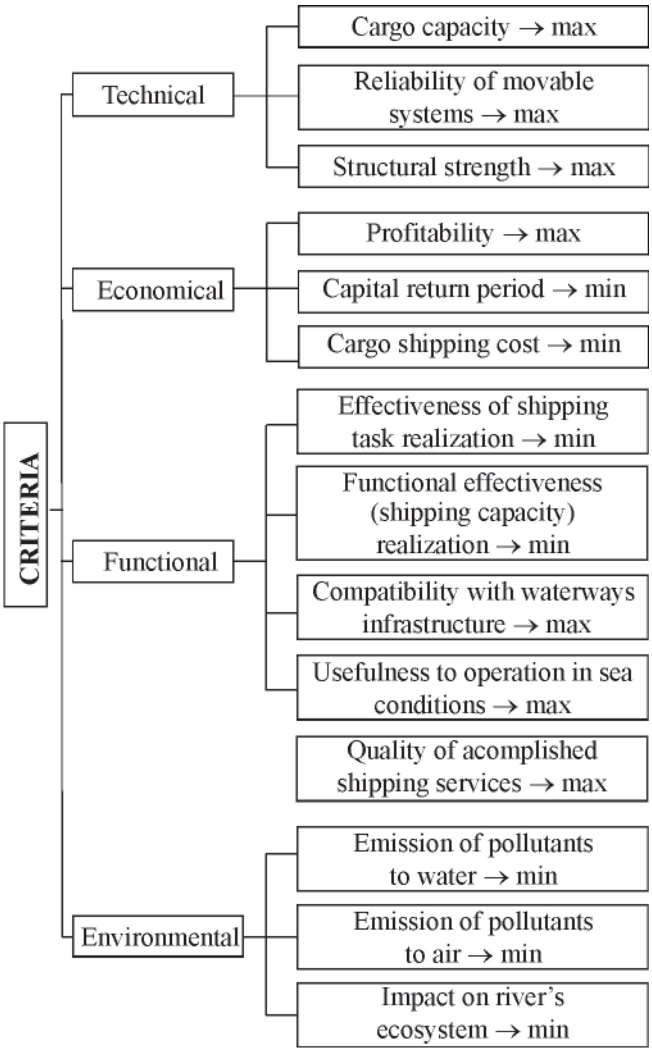



*__Fig. 2.__ Set of criteria for assessing the acceptability of SRM fleet structures.*
*__Source__: The author's concept*

## MATHEMATICAL MODEL OF FUNCTIONING THE FLEET OF RIVER-SEA SHIPS

### *Decision variables in the mathematical model of functioning the fleet of river-sea ships*

The mathematical model of functioning the river-sea ships can be elaborated in compliance with the principles presented by Tarnowski [6]. The first step in building such model is to determine parameters and decision variables. In the case in question for each of the schemes of operation of such ships the following can be distinguished:

- Assumed parameters, namely:
  - rate of cargo flow – W [mln t/year]
  - length of shipping route – S [km]
  - port cargo handling capacity – $Z_p$ [t/day]
  - season (of the year) - $S_z$ [-].
- Searched decision variables, namely:
  - type of ship (bulk cargo carrier, tanker, versatile river-sea ship)
  - Cargo carrying capacity (permissible mass of shipped cargo) – $M_{lad}$ [t]
  - ship speed – V [km/h]
  - number of ships necessary to cope with cargo flows on a given shipping route – $n_{s_i}$ [units/year].

### *Limitations in the mathematical model of functioning the fleet of river-sea ships*

In the mathematical model of functioning the river-sea ships - for the reason of a large number of investigated variants and a broad range of parameters of cargo flows – definite areas of planned investigations should be distinguished, including teh following:

- possible solutions for SRM fleet
- permissible solutions for SRM fleet.

Geometry of area of possible solutions results from rates and directions of cargo flows. Geometry of area of permissible solutions results from real situation on both waterways and market of transport services.

Limitations of the mathematical model of functioning the river-sea ships can be divided into:

- qualitative ones,
- quantitative ones.

Qualitative limitations have been already systematized in Fig. 3, and quantitative ones are as follows:

- concerning SRM fleet:
  - maximum permissible shipping period, according to shipping task – $T_{Pmax}$ [days]
  - minimum possible frequency of ship arrivals to port, according to structure of the fleet – $n_{w_{min}}$ [units/day]
  - maximum permissible ship deadweight on a given route, according to river bed parameters – $DWT_{max}$ [t]
  - maximum permissible ship speed on a given waterway, according to navigation standards – $V_{max}$ [km/h]
  - maximum permissible cargo shipping cost, according to requirements of orderers – $KT_{max}$ [€/(t*km)].
- concerning cargo flows:
  - both maximum and minimum permissible amount of cargo shipments accepted on ship board, their masses and volumes, according to shipping tasks.

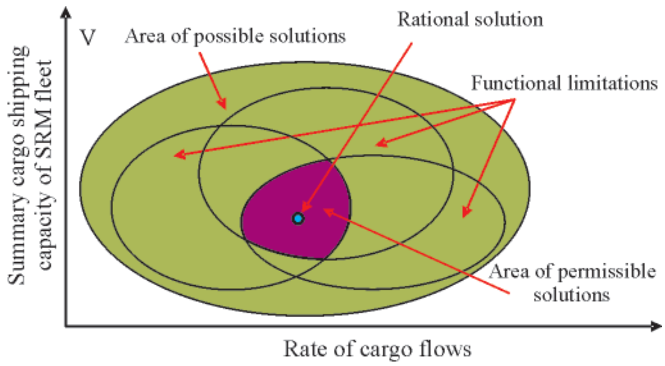



*__Fig. 3.__ Example geometry of areas of possible and permissible solutions of SRM fleet functioning.*
*__Source__: The author's concept*

### *Mathematical description of functioning the SRM fleet. Functional criteria and their place in the model*

The mathematical model of the river-sea ships' functioning constists in checking the effectiveness of the conditions for SRM fleet structure in compliance with the following functional criteria:

**A. Functional effectiveness according to the „point-to-point"principle**

**General assumptions**:
The functional effectiveness of every SRM group incorporated to the fleet's structure should be maximum:

$$\sum_i E_i \to \max \tag{1}$$

under the condition:

$$\sum_i E_i \geq W \tag{2}$$

where:

$W$ – assumed cargo flow rate [mln t/year]

$\sum_i E_i$ – functional effectiveness (shipping capacity) of SRM fleet [mln t/year].

And, necessary values of the criterion should be determined by using the following relationships:

$$\sum_i E_i = n_{s_i} \cdot n_{r_i} \cdot M_{lad_i} \tag{3}$$

$$n_{r_i} = \frac{(365 - t_{rm})}{T_{p_i}} \tag{4}$$

where:

$n_{s_i}$ – number of river-sea ships of i-th group, necessary to cope with cargo flows on a given shipping route [ships/year]

$n_{s_i}$ – number of voyages possible to be performed by i-th group of ships during one year [voyages/year]

$M_{lad_i}$ – permissible mass of cargo shipped on board the ships of i-th group [t]

$t_{rm}$ – duration time of repairs, inspections [days]

$T_{p_i}$ – duration time of cargo shipping by the ships of i-th group [days].

Types of shipping tasks:

a) DCS and CSSCS group

$$T_p = (t_r + t_p) \tag{5}$$

where:

$t_r$ – calculated period of river-sea ship's voyage [days]

$t_p$ – calculated period of river-sea ship's port lying [days].

And:

$$t_r = \frac{S}{V} \tag{6}$$

$$t_p = \frac{M_{lad}}{Z_p} \tag{7}$$

where:

$S$ – assumed length of shipping route [km]

$V$ – required service speed of river-sea ship [km/h]

$M_{lad}$ – permissible mass of shipped cargo [t]

$Z_p$ – assumed cargo handling capacity of port [t/day].

b) CSDS and CSMSR group

$$T_p = \sum_{i=1}^{n} (t_{r_i} + t_{p_i}) \tag{8}$$

where:

$t_{r_i}$ – period of i-th voyage [days]

$t_{p_i}$ – period of i-th lying in i-th port [days].

And:

$$t_{r_i} = \frac{S_i}{V_i} \tag{9}$$

$$t_{p_i} = \frac{\Delta M_{lad_i}}{Z_{p_i}} \tag{10}$$

where:

$S_i$ – length of i-th section of shipping route [km]

$V_i$ – ship speed over i-th section of shipping route [km/h]

$\Delta M_{lad_i}$ – mass of cargo handled in i-th port [t]

$Z_{p_i}$ – assumed cargo handling capacity of i-th port [t/day].

**B. Effectiveness of shipping task accomplishment according to the „just-in-time"principle**

**General assumptions**:

Effectiveness of shipping task accomplishment should be maximum provided it does not exceed the period given in the shipping agreement:

$$S_p \to \max \tag{11}$$

under the condition:

$$T_p \leq T_u \tag{12}$$

where:

$S_p$ – effectiveness of shipping task accomplishment [-]

$T_p$ – cargo shipping period [days]

$T_u$ – cargo shipping period given in the shipping agreement [days].

Types of shipping tasks:

a) For the groups: DCS and CSSCS $T_p$ value should be determined on the basis of the relation (5).

b) For the groups: CSDS and CSMSR $T_p$ value should be determined on the basis of the relation (8).

**C. „Shipping service quality" according to the ALARP priciple**

Quality of shipping service should be maximum:

$$Q \to \max \tag{13}$$

under the condition:

$$Q \geq Q_{wp} \tag{14}$$

where:

$Q$ – shipping service quality (percentage of cargo mass accepted by cargo receivers without any claims as to its state) [%]

$Q_{wp}$ – required quality of shipping service [%].

The shipping service quality can be considered as a risk of non-fulfillment of client's demands contained in the shipping agreement. It should be lower than an acceptable risk level estimated by underwriters on the basis of the following factors: ship age, crew experience, crew certificates, date of survey, failure statistics etc. Risk is the product of failure probability and loss resulting from the failure.

Therefore:

$$R_{su} \geq R^n_{wp} \tag{15}$$

where:

$R_{su}$ – risk level estimated by underwriters [mln €]

$R^n_{wp}$ – risk of non-fulfilment of client's demands [mln €]

hence:

$$P_{su} * S_{su} \geq P^n_{wp} * S^n_{wp} \tag{16}$$

where:

$P_{su}$ – probability of failure occurence during accomplishment of shipping service (estimated by underwriters) [%]

$S_{su}$ – possible financial loss suffered by underwriters [mln €]

$P^n_{wp}$ – probability of non-fulfilment of client's demands [%]

$S^n_{wp}$ – possible loss sufferred due to non-fulfilment of client's demands [mln €].

And:

$$P_{su} > P^n_{wp} \tag{17}$$

$$S_{su} > S^{n}_{wp} \quad (18)$$

$$P^{n}_{wp} = P^{n}_{lad} * P^{n}_{t} * P^{n}_{m} \quad (19)$$

where:

- $P^{n}_{lad}$ – probability of not coping with demanded shipping service quality (cargo delivery associated with claims as to its state from the side of its receiver([%]
- $P^{n}_{t}$ – probability of non- delivery of cargo to its receiver within a given period [%]
- $P^{n}_{m}$ – probability of non- delivery of cargo to its receiver to a given place [%].

Each of the probabilities can be realized independently to other ones. Therefore the product (19) is valid.

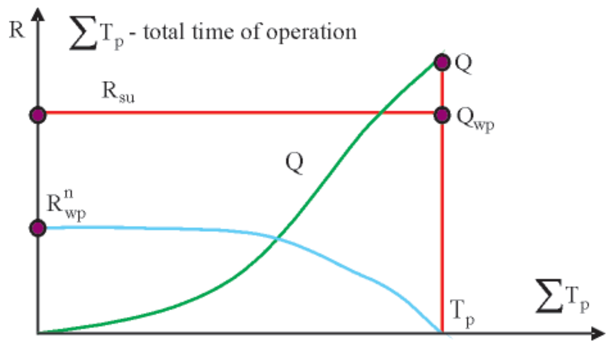



***Fig. 4.** Example of an acceptable shipping variant with a view of shipping risk. **Source**: The author's concept*

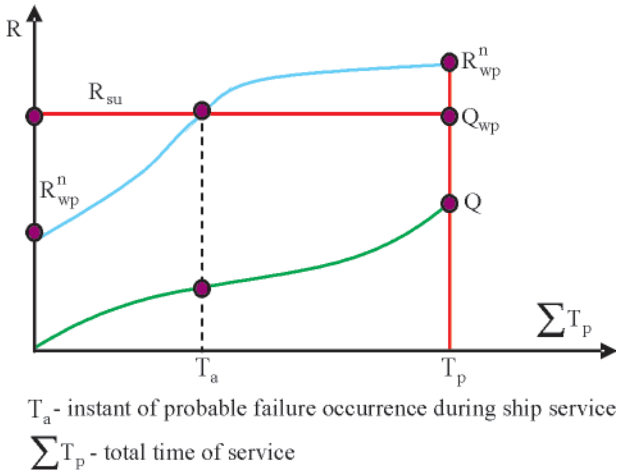



***Fig. 5.** Example of an unacceptable shipping variant with a view of shipping risk. **Source**: The author's concept*

Hence, the probability of fulfilment of conditions of demanded shipping service quality ($P_{wp}$) is equal to:

$$P_{wp} = 1 - P^{n}_{wp} \quad (20)$$

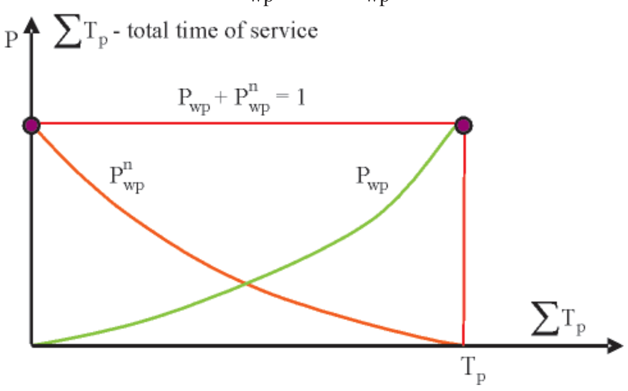



***Fig. 6.** Example of dynamic changes in probabilities of fulfilment or non-fulfilment of conditions of demanded shipping service quality. **Source**:The author's concept*

The above presented kinds of probabilities are directly connected with safety of river-sea ships. According to J. Semenov [5], in order to determine their values, it is necessary to apply - to failure risk estimation practice - such characteristics which would be capable of ensuring objective control of shipping service quality to the ships in question. Statistical indices are suitable to solve the problem. They are formulated on the basis of statistical information and characterize a safety level of existing river-sea ships regarding causes which have led to failure of any particular ship. They can be divided into absolute and relative ones.

*Absolute statistical indices*

Such indices are formed to estimate safety level of transport units within a given period of their operation (year, month etc(. These are a.o.:

- number of failures of a considered type of ships, and associated casualties
- number and deadweight of lost ships of a considered type, and associated loss of property
- number and value of lost cargo, and associated loss of profits
- size of pollution resulting from failures and associated cost of its liquidation etc.

*Relative statistical indices*

Such indices are formed to estimate safety level related to absolute statistical data. These are a. o. as follows:

- number of voyages of failed river-sea ships versus their total number
- amount of cargo shipments accepted with claims as to their state versus their total amount
- duration time and length of voyages of failed ships versus total period of their service.

The relative failure frequency indices can be used to assess the achieved levels of:

- safety of operation of river-sea ships
- service life of ships of a considered type
- technical perfectness of shipboard, power and technological devices installed on river-sea ships
- professional preparedness and discipline of crews of river-sea ships
- organization and support of rescue actions.

The main value of the specified statistical indices is its objectiveness. Though they possess many important drawbacks, e.g.:

- they reflect only past events
- they can not be fully used for solving distant-future tasks.

To analyze causes of failure frequency is necessary because of possible multiple factors disturbing safe navigation modes.

*Failure frequency characteristics according to causes of failure occurrence*

On the basis of such characteristics it is possible to objectively assess navigation safety of river-sea ships as compared with other types of failure frequency due to a given cause during a given period (year, month etc). A set of such characteristics should be formed on the basis of the following principles:

- every characteristic is reperesented by probability distributions of its parameters in all modes of functioning the SRM
- probability of passing the river-sea ship into failure functioning mode is reflected by occurrence of endangering factors which can be of subjective or objective character

- possibility of recovering the safe functioning modes of river-sea ships should be assess depending on adequacy of resources planned to be used for normalizing the functioning mode of a given type of ships (such resources can be of technical, organizational, social and legal character).

## *Economic criteria used in the functional model of the SRM fleet*

In order to select one rational solution, out of possible variants, it is necessary to perform an economical analysis in which economic criteria will be taken into account. For the reason of reaching the information certainty level which has been usually faced, the following criteria seem to be most effective:

**A**. expected profitability of shipping services - Z [mln €], and Z → max

**B**. predicted return period of invested capital - PBP [years], and PBP → max

**C**. cargo shipping cost -KT [€/(t*km)], and KT → min.

**A.** The profitability of river-sea ships can be determined on the basis of the following relationship:

$$Z = WE - KE \tag{21}$$

where:

WE – expected incomes form the SRM fleet operation [mln €/year]

KE – operational cost of the SRM fleet [mln €/year].

The above mentioned incomes can be determined on the basis of the relationships:

$$WE = n_{s_i} * M_{lad_i} * n_{r_i} * f_r \tag{22}$$

$$f_r = S * f_{r,j} \tag{23}$$

where:

$f_r$ – freight rate [€/t]

$f_{r,j}$ – unit shipping rate [€/t*km].

The quantities: $n_{s_i}$, $M_{lad_i}$, $n_{r_i}$ have been already defined in page 7 (3).

Yearly operation cost of the SRM fleet can be determined on the basis of the relationship:

$$KE = (KZ + KB) * n_{s_i} \tag{24}$$

where:

KZ – cost of invested capital return [mln €/year]

KB – current maintenance costs of one river-sea ship [mln €/year].

The cost of invested capital return can be determined from the following relationship:

$$KZ = CR\left[KI - KZŁ(1-i)^{-e}\right] \tag{25}$$

$$CR = \frac{(1+i)^e \cdot i}{(1+i)^e - 1} \tag{26}$$

$$KI = 4.12 + 0.010369 \cdot DWT^{0.717338} \pm \Delta_1 \tag{27}$$

where:

CR – coefficient of invested capital return period [-]

KI – investment cost of river-sea ship [mln €/year]

KZŁ – price of a ship excluded fom service, equivalent to its scrapping value [mln €]

i – credit interest per year [%]

e – credit payback period [years]

$\Delta_1$ – correction for specificity of river sea ship ($\Delta_1 = \pm 0.14$) [mln €].

Eq. (27) was elaborated on the basis of worldwide prices of cargo ships of main types [CTO (Ship Design and Research Center, Poland) Market information].

On the basis of information published in the *Shiprepair* journal in the years 1999-2006 it can be assumed that:

$$KZŁ = 0.1 \cdot KI \pm 0.007 \tag{28}$$

The current costs can be determined from the following relationship:

$$KB = KBZ + KBK + KBU + KR \tag{29}$$

where:

KBZ – personnel costs (crew wages and boarding) [mln €/year]

KBK – repair and maintenance costs [mln €/year]

KBU – ship and cargo insurance costs [mln €/year]

KR – ship operation expenditures [mln /year].

It can be assumed that:

$$KBZ = \frac{k_1 \cdot n_{zal} \cdot w}{10^6} \tag{30}$$

$$KBK = k_2 \cdot KI \tag{31}$$

$$KBU = 0.022 \cdot (KI)^{0.99} \tag{32}$$

$$KR = KRP + KRO \tag{33}$$

where:

$k_1$ – number of month of labour of one crew memeber [months]

$n_{zal}$ – required number of crew members [persons]

w – mean monthly wage of one crew member [€]

$k_2$ – coefficient of repair and maintenance costs [-]

KRP – costs of propulsion fuel oil [mln €/year]

KRO – costs of ship servicing in ports (inluding: charges for: cargo handling, port servicing and agent's servicing) [mln €/year].

And:

$$KRP = \frac{t_r \cdot n_r \cdot h_{pal} \cdot C_{pal}}{10^6} \tag{34}$$

$$KRO = \frac{t_p \cdot n_p \cdot \beta \cdot GT + \chi \cdot M_{lad}}{10^6} \tag{35}$$

where:

$t_r$ – calculated period of voyage of river-sea ship [days]

$t_p$ – calculated period of port lying of river-sea ship [days]

$n_r$ – number of voyages of river-sea ship per year [units/year]

$h_{pal}$ – assumed fuel consumption per hour [t/h]

$C_{pal}$ – assumed fuel price [€/t]

$n_p$ – number of port-lyings of river-sea ship per year [units/year]

β – assumed port service charge [€/t]

GT – designed gross register tonnage of river-sea ship [t] (Fig. 7)

χ – assumed cargo handling charge [€/t].

It can be assumed that:

$$n_p = k_3 \cdot n_r \tag{36}$$

$$h_{pal} = N \cdot h^j_{pal} \cdot 10^{-6} \tag{37}$$

$$N = \frac{D^{\frac{2}{3}} \cdot V^3}{C} \tag{38}$$

where:

$k_3$ – coefficient of shipping task complexity [-]
N – designed output of river-sea ship power plant [kW]
D – designed displacement of river-sea ship [t]
V – required service speed of river-sea ship [km/h]
$h^j_{pal}$ – assumed specific fuel oil consumption during ship voyage [g/kWh]
C – Admiralty coefficient [-] (Fig. 8).

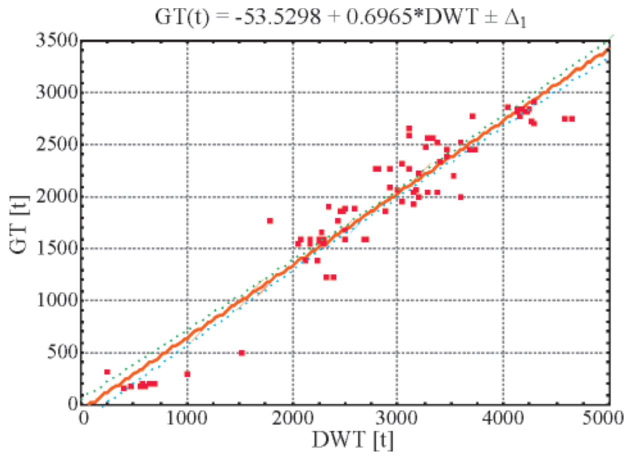



***Fig. 7.*** *The relationship: GT = f(DWT).* ***Source****: the author's elaboration*

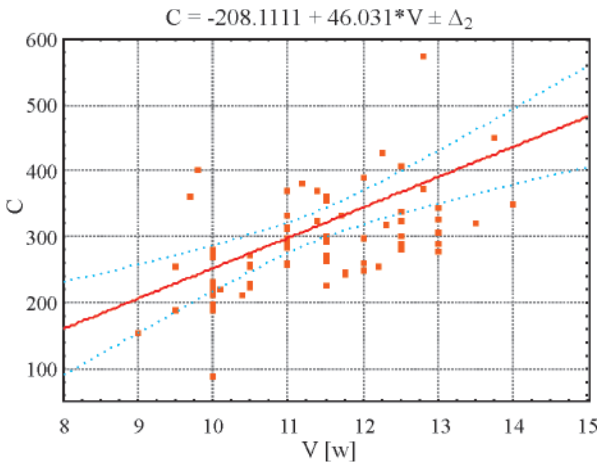



***Fig. 8.*** *The relationship: C = f(V).* ***Source****: the author's elaboration*

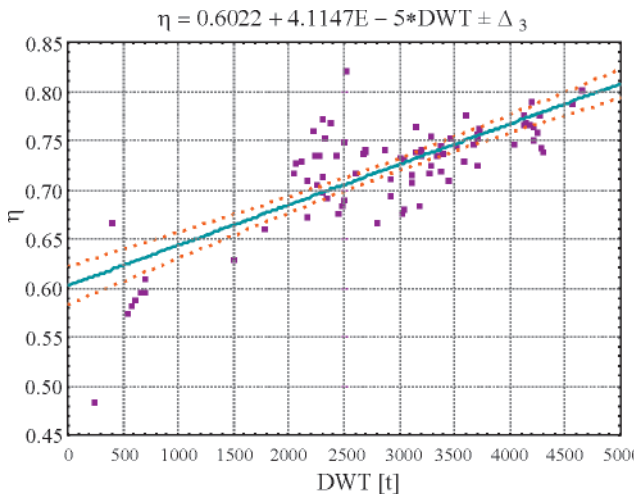



***Fig. 9.*** *The relationship: η = f(DWT).* ***Source****: the author's elaboration*

The ship displacement D can be determined on the basis of the following relationship:

$$D = \eta \cdot DWT \tag{39}$$

where:

η – deadweight factor of river-sea ship (Fig.9)
DWT – designed deadweight of river-sea ship [t].

And:

$$DWT = q * M_{lad} \tag{40}$$

$$DWT \le DWT_{max} \tag{41}$$

where:

q – a calculation coefficient: q = 1.10 ÷ 1.20 [-]
$DWT_{max}$ – maximum permissible deadweight of ship on a given shipping route [t].

**B.** The second economic criterion, i.e.the invested capital return period PBP [years], can be determined from the relationship:

$$PBP = \frac{KI}{Z} \tag{42}$$

Values of the quantities Z and KI can be determined by using the relation (21) and (27).

Values of the capital return period parameters show investment profitability levels.

The period should be as short as possible and not exceed 5 – 7 years.

**C.** The third criterion, i.e. the cargo shipping cost KT [€/(t*km)], can be determined on the basis of the following relationship:

$$KT = \frac{KE}{n_s * M_{lad_r} * S_r} \tag{43}$$

where:

$n_s$ – number of ships necessary to cope with cargo flows on a given shipping route [ships/year]
$M_{lad_r}$ – mass of cargo shipped by one ship during one year [t]
$S_r$ – length of route covered by one ship during one year [km/year].

And:

$$M_{lad_r} = M_{lad} * n_r \tag{44}$$

$$S_r = S * n_r \tag{45}$$

## CONCLUSIONS

In order to select a concrete shipping strategy which has to be used in river-sea shipping system it is necessary to elaborate in advance a functional model of fleet of river-sea ships. Its elaboration allows to preform simulations which can serve for assessing and checking the following items:

- ❍ parameters of functioning the ships on a given route in compliance with a shipping task elaborated in line with current rate of cargo flow along the considered route
- ❍ flexibility of the functional model regarding changes in rates and directions of cargo flows according to their short-term and long-term predictions.

The elaboration and analysis of such model can be applied to:

- ❍ An appropriate choice and adjustment of:
  - ✓ shipping task depending on market demand considered in the form of cargo flows
  - ✓ rational scheme of SRM fleet functioning, depending on selected shipping tasks and waterways infrastructure parameters.

❍ Determination of design assumptions for river-sea ships intended for operation in European system of water transport corridors, including:
  - ✓ number of ships necessary for realization of shipping tasks, i.e. structure of the ships' stock
  - ✓ service speed values of the ships of particular types
  - ✓ cargo capacity values (volume of holds) of the ships of particular types.

❍ Choice of cargo shipments for a selected shipping scheme, depending on operational features of the ships, season of the year etc.

Investigation of the functional model results in determination of technical assumptions for design of particular river-sea ships.

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**CONTACT WITH THE AUTHOR**


Magdalena Kaup, Ph. D.
Faculty of Marine Technology
Szczecin University of Technology
AL. Piastów 41,
71-065 Szczecin, POLAND
e-mail: mkaup@ps.pl
phone: (091) 449 - 47 - 50