# GRAPH MODEL OF MATERIAL ARRANGEMENT ON THE SHIPS HULL AND ITS SOLUTION BY THE SUB-OPTIMAL CHAIN METHOD

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## ABSTRACT

The article discusses optimisation task of vessel hull steel distribution by means of graph model. Optimal and sub-optimal options as far as the dimensioning and steel grades are concerned are found by means of linear programming methods; Dejikstra or Ford-Fulkerson flow algorithms. The suggested method has been used for economically effective solution of heightened strength shipbuilding steel and corrosion-proof steel utilisation for operating train-ferries and those being designed.

## INTRODUCTION

A ship's steel hull is a complicated system of joined components (metal sheets, rolled shapes, welded joints etc.) each of which may have different dimensions and be made from different types of steels. During a ship's design, building and repair it is often necessary to select steel grades and dimensions.

Another problem to be solved is making a Metal Order List for shipyards and commercial studies for expedient search of mostly favourable customers among steel enterprises or dealers - forms as far as the delivery of shipbuilding steel is concerned.

By combining a model of a ship hull with accepted criteria for economic effectiveness it is possible, via the use of linear and non-linear programming to calculate a rational distribution of materials throughout the hull.

In order to function properly and reach the optimal solution the model should satisfy the following requirements:

- It must contain data on rather a large number of components and welds, which are the most critical areas of construction.
- It must allow the introduction of various restrictions arising from the multi-criteria nature of the problem and the requirements of normative documents.
- It must search for the optimal variant using highly efficient mathematical programmes.
- It must be able to find sub-optimal solution variants to expend to give the designer options which to base the final decision.
- It should have an addictive nature to make it possible to conduct the analysis when passing constructive regions of the hull in a consecutive, step-by-step manner.

In practice it can be assumed that substitution of one steel to another during a search for the best solution would not lead to major structural changes but only to changes of cross-sectional dimensions of components.

This allows the problem to be linearized i.e. to use methods of linear programming. A mathematical model of material distribution throughout the ship hull in this case has a considerable advantage - it allows the use of well known algorithms possessing high computational capacity [1].

The graph model satisfies the above - mentioned requirements and provides a clear basis on which a designer can work more efficiently.

## GRAPH BUILDING

The hull is subdivided into separate construction regions (CR) or details along the midship section and length depending on its function and wear during operation (Figures 1 and 2). Production expediently of detail manufacturing from different steels is also evaluated. Units (CR) found in this way and numbered when building the network are located along a horizontal line allowing their continuos sequencing. The vertical division of network components is performed according to the range of steels considered. As a result a weighted graph is formed which is convenient for calculation of many technical and economical hull characteristics. The characteristics end construction region are assigned to graph vertexes, and to arcs - characteristic of a welded joint between two CRs (cost, labour consumption etc.).

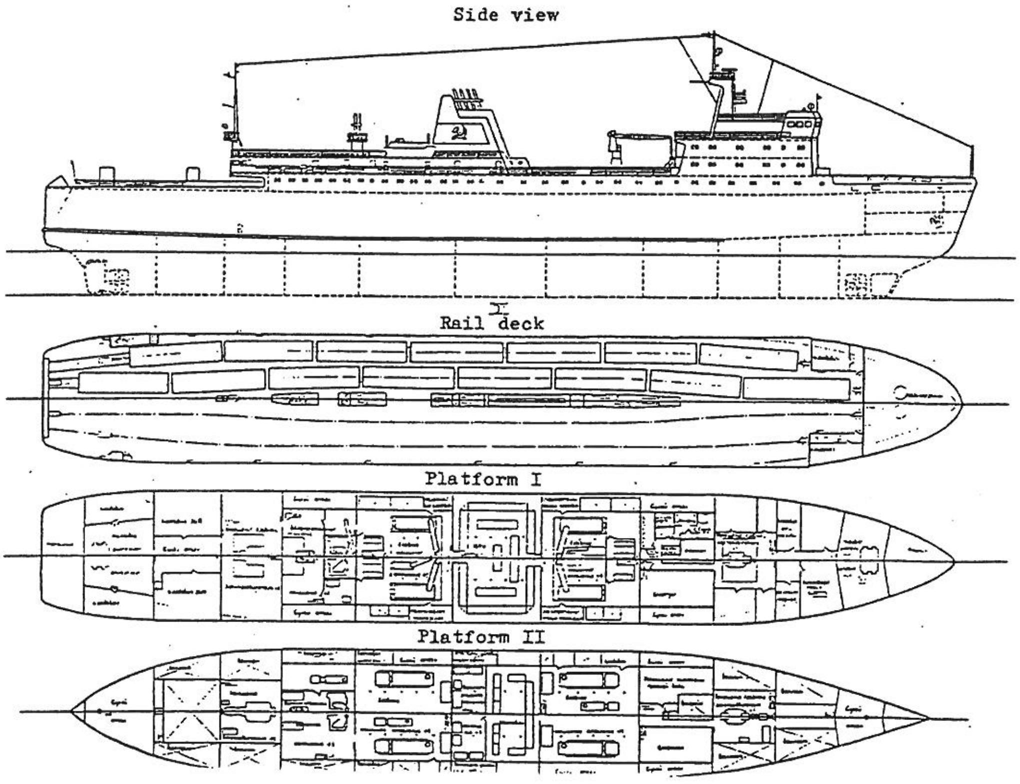

*Fig. 1. Dividing the hull of a train-ferry into designing block units for the graph model building procedure. Train-ferry "Sakhalin" (new generation) Maritime Register of shipping class KM YL 1 A2 (L x B x T = 116,4 x 19,5 x 6,2 m, DW = 2245 t).*

System construction, information support and solution can be realised by the following steps:

- analysis of hull damage of ships prototypes and hull division into design units
- division into construction regions subject to wear due to an identical reason having similar load character and function, etc.
- identification of the most probable range of steels used
- formulation of the data bank and preliminary information flow, calculation of

thickness of framing and plating, consideration of RF Register and valid standards requirements, testing of frame components on effect of factors leading to damage

- steel grades elimination of vertices (steel grades - hull regions) not satisfying the requirements of standards, specifications and operation conditions
- selection of optimisation criteria
- procedures of optimisation of steel distribution, identification of optimal and sub-optimal variants.

Any solution must satisfy some certain construction and technological restrictions which may be of an absolute character, e.g. dependent on strength, stiffness, corrosion resistance, maintenance reliability, or of relative character, e.g. depending on contact compatibility of components. For instance, a large difference of shell plate thickness is not desirable or steel grades can have poor compatibility in relation to their wear.

## THE MATHEMATICAL INTERPRETATION OF THE GRAPH MODEL

Let the set of hull components be:

$$C = c\left\{ c_a \,\middle|\, \alpha = 1, \overline{\delta} \right\} \quad \left(\delta = |C|\right) \tag{1}$$

The components are enumerated in the “connected” manner which means that the components $c_\alpha$ and $c_{\alpha+1}(\alpha = 1, \bar{\delta} - 1)$ must be adjacent and thereby the one-dimensional scanning of the hull is made thereby possible.

The set of steel grades is:

$$S = \left\{ s_\beta \,\middle|\, \beta = 1, \overline{\sigma} \right\} \quad \left(\sigma = |S|\right) \tag{2}$$

Consider the Cartesian product:

$$C \cdot S = \left\{ \left\langle c_\alpha, s_\beta \right\rangle \,\middle|\, \alpha = 1, \bar{\delta}, \beta = 1, \overline{\sigma} \right\} \tag{3}$$

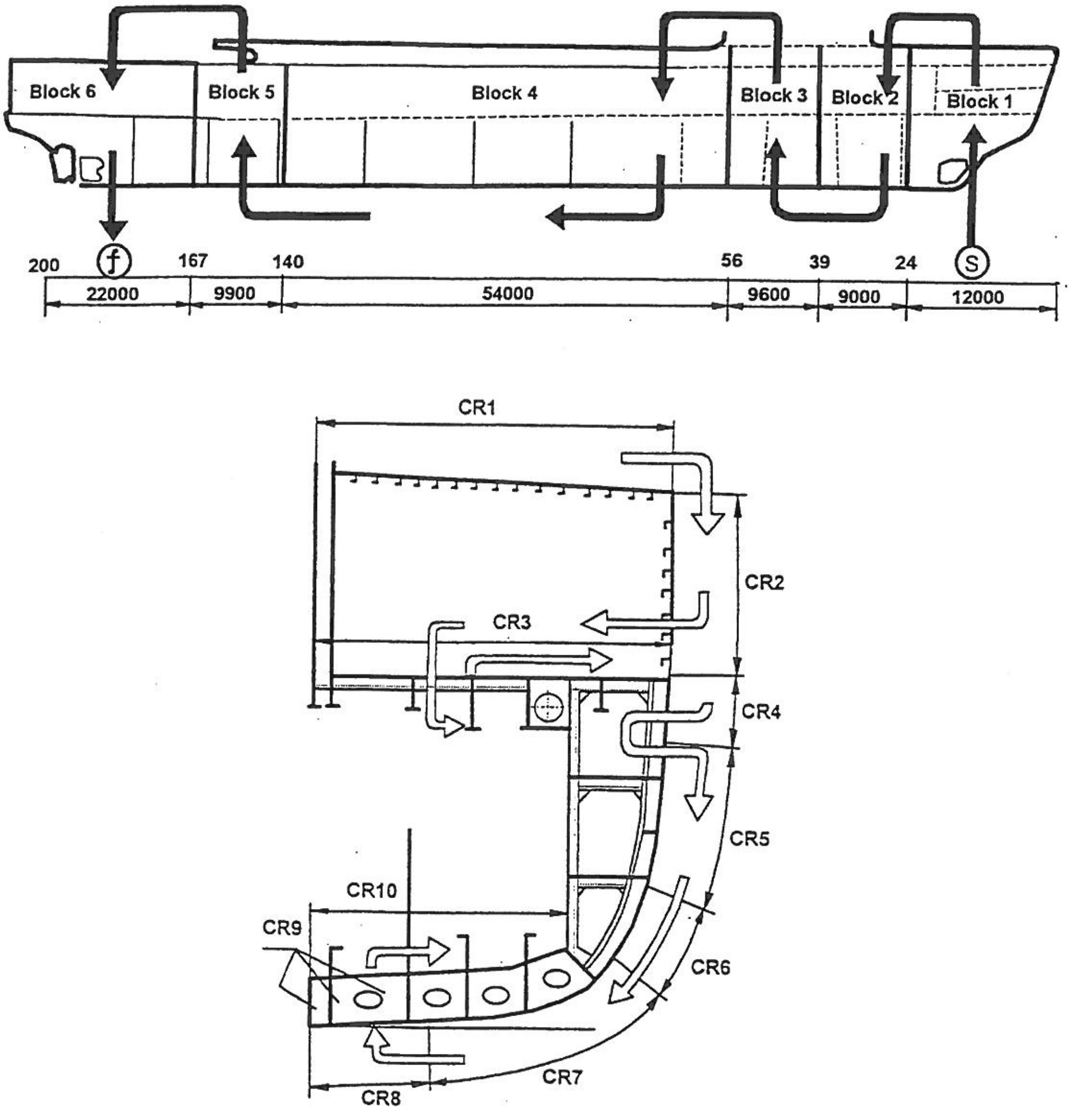

*Fig. 2. Dividing the hull of a train-ferry into designing block units for the graph model building procedure.*

- *Side view of the hull. An order of movement along the vessel hull while optimising by means of the shortest path method (Dejikstra algorithm): s - source of the network, f - finish, t - file.*
- *Midship cross-section, CR - constructional region.*

The restrictions of the first class above (absolute ones) prohibit certain combinations in this set. The rest of the combinations (the feasible ones) are considered as the vertices of certain graph. The restrictions of the second class (contact compatibility) prohibit some arcs of the graph interpreting conditions of compatibility.

If the component $c_\alpha$ may be made of steel $s_\beta$ and at the same time the component $c_{\alpha+1}$ may be made of the steel the $s_\beta$ then the arc from $\langle c_\alpha, s_\beta \rangle$ to $\langle c_{\alpha+1}, s_\beta^{1} \rangle$ is introduced. The length of every such arc is summed up of the two parts: the first part is the price of making component $c_\alpha$ of the steel of grade $s_\beta$ while the second - the price of welding together the components $c_\alpha$ and $c_{\alpha+1}$ made of the steel grades $s_\beta$ and $s_{\beta'}$ respectively. The price should be understood in a broad sense according to the above-said conditions.

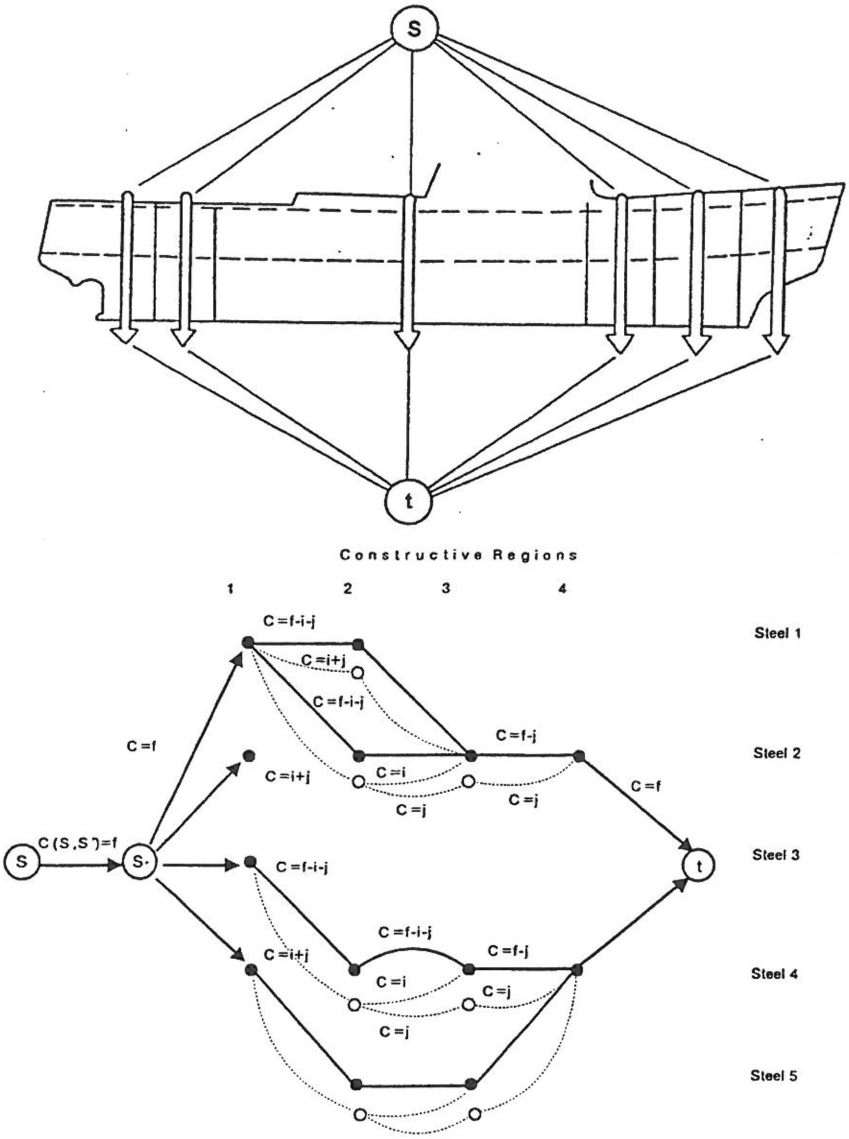

*Fig. 3. The graph - model for optimal distribution of steel ($s_\alpha$) by means of Ford-Fulkerson algorithm.*

- *The flow motion from f - units through hull blocks.*
- *A part of the flow task graph: c - ark carrying capacity, f - quantity of the flow units (hull blocks), i-j - a number sequence of hull structural portions and s - steel grades.*

Vertices of the kind $\langle c_\alpha, s_\beta \rangle$ correspond to the two special ones - START and FINISH. START is connected to every vertex $\langle c_1, s_\beta \rangle$ by arcs equal to zero.

Arcs $\langle c_\delta, s_\beta \rangle$ connected to vertex FINISH are equal to the price of making component $c_\delta$ of steel $s_\beta$.

As a result we obtain a graph model of the hull:

$$
\begin{array}{ll}
G = \langle V, E, L \rangle & \text{where:} \\
V = \{ v_1, v_2, \ldots, v_{n-1}, v_n \} & \text{- the set of vertices,} \\
E = \{ e_1, e_2, \ldots, e_{n-1}, e_n \} & \text{- the set of vertices,} \\
L = [ e_j ] & \text{- is the length of the j - th arc.}
\end{array}
\qquad (4)
$$

The graph is multipartite and acyclic Let's consider for convenience the vertices $v_i$ and $v_n$ as START and FINISH, $v_1 = \langle c_\alpha, s_\beta \rangle$ respectively, and let all the vertices be enumerated in acyclic manner. It is sufficient to this end to enumerate vertices in the lexicographic order with respect to the components and steel grades numeration, which means that if $v_i = \langle c_\alpha, s_\beta \rangle$ and $v_{i'} = \langle c_\alpha, s_{\beta'} \rangle$, then $I < i'$ implies $\alpha < \alpha'$ or $\alpha = \alpha'$, but $\beta < \beta'$.

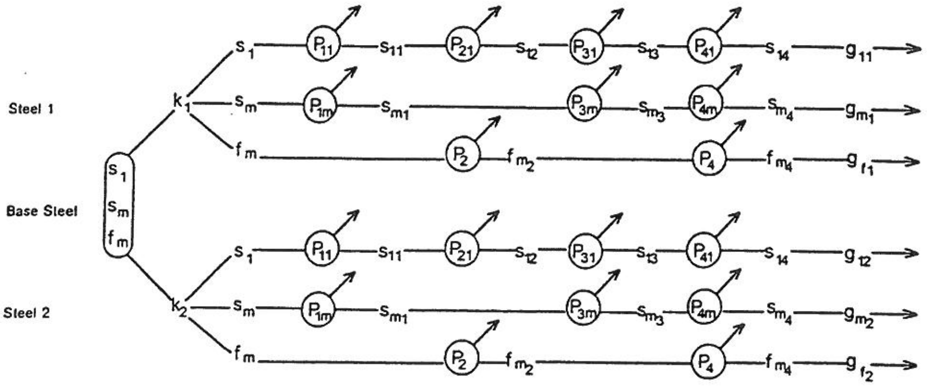

*Fig. 4. The graph - model for optimal distribution of steel ($s_\alpha$) by means of Ford-Fulkerson algorithm. Algorithm making for database formation for the hull details thickness ($s_m$) and profile section ($f_m$). Introduction of limitation system according to Classification Society Rules.*
*$P_{1\text{-}4}$ - along the minimum thickness, stability, stiffness dimensions according to the standard etc. and*
*k - transition coefficient - material factor according to the Rules.*

The structure of the graph model is then interpreted as follows: any path in the graph from START to FINISH correspond to a certain arrangement of material on the ship's hull. If the vertex $\langle c_\alpha, s_\beta \rangle$ is situated in the path, then there are no vertices the path of the kind $\langle c_{\alpha'}, s_{\beta'} \rangle$ where $\beta \neq \beta'$, which means that the component $c_\alpha$ should be made of steel of grade $s_\beta$.

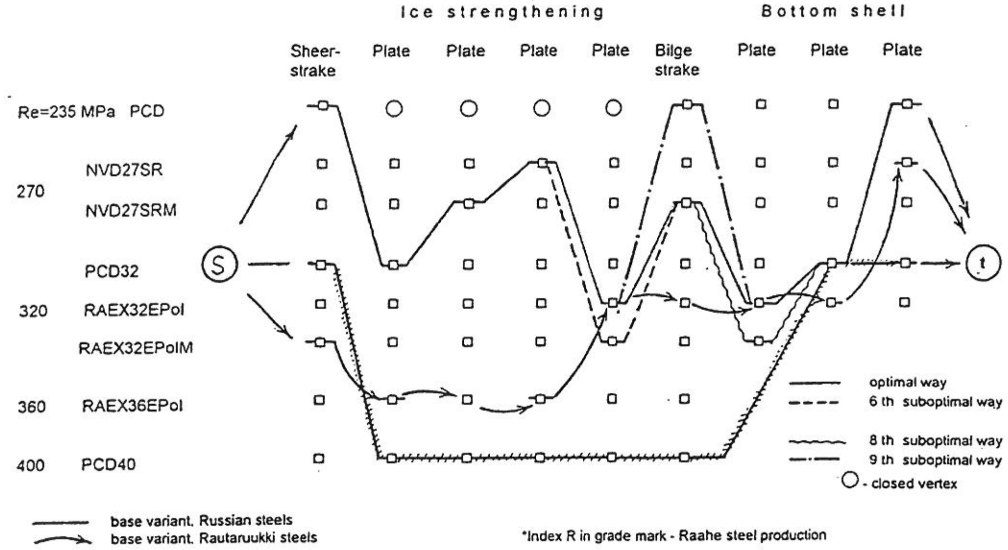

*Fig. 5. Part of the graph for the middle block of the "Sakhalin" ferry hull. Optimal and sub-optimal variants of shipbuilding steel distribution.*

The problem of model optimisation by an economic, for example minimisation of total expenses for construction and repair, may be put now as a problem of finding the shortest path from START to FINISH in the graph G [3].

The graph model for one of the hull blocks is represented in Fig 5.

Only those arcs which are part of certain variant of material arrangement are depicted in the figure.

The complete pattern includes all the arcs connecting every vertex of the kind $\langle c_\alpha, s_\beta \rangle$ to every vertex of the kind $\langle c_{\alpha'}, s_{\beta'} \rangle$ excluding arcs from "closed sectors" (see Fig. 5).

## INTRODUCING A SYSTEM OF RESTRICTIONS - NON-COMPLETENESS OF THE GRAPH MODEL

The database for hull components used in the model is processed by input of a system of restrictions:

- minimum thickness of plates in certain regions according to the rules of the Classification Societies with provision minimum section modulus of a hull
- thickness of the collapsible frame to provide for stability condition
- thickness to achieve fatigue durability
- thickness to avoid plastic deformation
- thickness and cross section surface area of profiles according to the size standards.

The graph model described above proves to be inadequate in the following two important aspects. For example some welded joints can not be taken into account since during the stepping sequences bow to stern some joints are not integrated by graph arcs. Nevertheless, the length of such joints is considerably less than those which do not cross the stepping direction and are therefore reflected in the graph. Therefore such welds do not play an essential role in the search for an optimal solution (Figures 1 and 6). The production programme of some steels can be limited and this factor is time - dependent: the situation with deliveries may change during the ship building cycle. It is possible to take into account both factors of non-completeness in the proposed model. Still it is not advisable since it complicates the model and makes it less understandable.

## FUNCTION OF THE TARGET - OPTIMISATION PROCEDURE

When constructing a graph model to each network vertex and arc a certain number is assigned corresponding to a real physical or cost value - graph metrics, which is a function of the target.

Selection of steel grades and their distribution should be optimised on the basis of metal consumption, building and repair expenses or income during the ship's life cycle. The aim is to find a compromise between these requirements.

The procedure of searching for optimal and sub-optimal solutions by minimum value of the target function correspond to the task of finding the shortest way on the graph from the vertex START to the vertex FINISH, or the task of the minimum cost flow. It is realised by using the Dejikstra or a modification of the Ford-Falkerson algorithms [3].

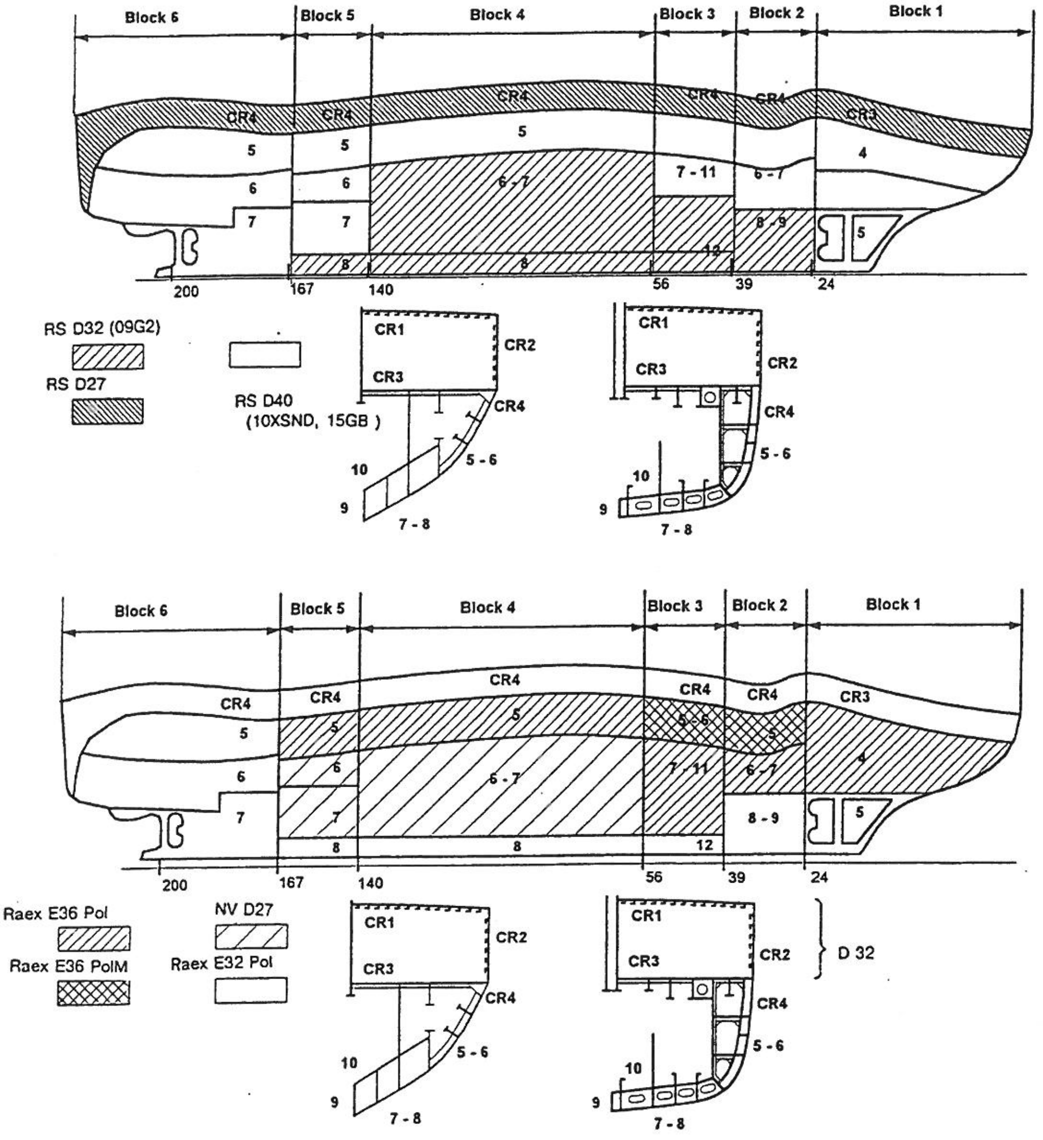

*Fig. 6. Shell plates of "Sakhalin" ferry. The optimal distribution of steel grades variant: upper - Base variant, lower - Optimal variant.*

## EXAMPLE OF MODEL APPLICATION

To prepare data on hull details it is necessary to divide the hull into blocks and construction regions (CR). The following drawings were taken for this work: general arrangements; shell plating expansion; hull cross sections. The hull is divided into six blocks by planes parallel to the midship section in regions of considerable structural change (system of framing and thickness). (See figures 2 and 4.)

Divisions into construction regions (CR) inside each block is performed according to whether the details have similar wear conditions or whether they will be made from the same type of steel or supplied by one manufacturer.

With the help of the graph model the efficiency of different combinations of steels for the hulls of the "Sakhalin" train-ferries [4] has been examined (Fig. 1).

Nowadays, ten such ships built in the period 1973-1989 are operating in the Far East on the Vanino-Holmsk crossing of the Tatarskiy channel.

The considerable experience regarding their operation that has been gained to this time allows the accuracy of the graph model to be estimate. More usefully, it allows the optimal selection of materials the second generation of replacement ships.

The wear of the hulls of the "Sakhalin" ferries is much greater than of cargo ships of the same class made of manganese steels. In some hull regions corrosion damage led to formation of the blowholes (heavy crevice corrosion).

As a result, during 10 years of operation the area of changes outer plating sheets reached 1870 $m^2$ per hull, and the number of repaired welds 1840 meters. Repair work led to heavy losses which arose due to the considerable costs of repair and profit losses due to interrupted ship operation. Changing of the outer ship plating and the other work led to ship dock repair time up to five months.

Reduced construction and repair costs for the hulls of the new generation of ferries, can be realised by selecting more corrosion resistant steels and filler materials and by the use of protectors or cathodic protection and special protective coatings.

Experience of operation of ships in the seas of the Far East shows that the use of all these methods is necessary. The large capital expense involved in the realisation of any technical solution emphasise the benefits to be gained by a comprehensive economic analysis of the life cycle of the ships with the method described above.

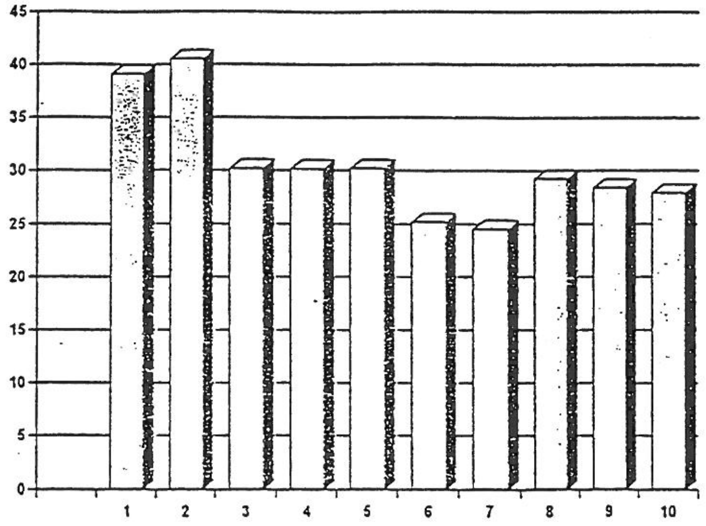

*Fig. 7. Forecast for the hull repair dock-time for comparable grade steels made by different metallurgical plants: 1-2 - base variants, traditional steel grades, 3,6-10 - corrosion resistant "POLAR" series of steels (Finland), 4-5 - combined variants, 6-7 - ordinary plate sizes (2000 x 7000 mm) and large plate sizes (2400 x 13000 mm) and 8-10 - sub-optimal variants.*

Data on the hull wear of ten ferries after 5-20 years of operation allows the regions subjected to the largest damage to be identified. On the basis of this data and the hull construction the hull is divided in areas of intensive weld corrosion such a way that almost all weld joints were represented as arcs in the graph are directly used in the optimisation calculations (Fig. 6).

The graph model thus built is well adapted to forecasting economic efficiency and life span of butt weld joints of the hull when using manual welding, submerged arc welding and gas shielded metal arc welding. It takes into consideration the cost of making the weld joints during ship hull construction, se well the cost of repair during the full life cycle of the ship hull.

Data related to graph arcs allows the factors affecting the economic parameters of weld joints[*] to be effectively taken into account.

That is:

- type and mode of welding
- type and diameter of electrodes
- type of weld joint
- durability of protective paint layers on the hull
- electric conductivity of sea water.

The graph model of the ferry's hull comprises 120 to 500 vertices and from 230 to some thousands of arcs depending on the number of steels grades used in the search for the optimal material distribution.

For example, with three types - 118 nods and 232 arcs
with four types - 234 nods and 756 arcs

Construction symmetry and identity of many details exclude the necessity to model of each of them by a individually. Nevertheless such a solution is also possible, but it would be accompanied considerable increase in model building and calculation time.

The well known Dejikstra algorithm was used to optimise the graph. The algorithm was specially modified to increase its calculation capacity and to provide the possibility of finding sub-optimal variants. The time for finding 10 solutions is not more than 3-5 minutes on PC 486.

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[*] Welds are arbitrarily subdivided in welds inside the construction regions and welds between CRs. If hull division is effected on the basis of details then there are no weld inside CRs. If A CR includes some large plates, then the number of internal welds exceeds the number of arcs. Cost indices of internal welds are related to graph vertices, i-e- they are summed with cost indices of construction regions. Cost indices of internal welds are related to graph vertices, i-e- they are summed with cost indices of construction regions.

*Table 1. Comparison of weight and cost parameters of the "Sakhalin" ferry with hull made of different steels and plate dimensions. Life cycle 25 years and 1995 price level.*

| Options | "Sakhalin - 1" (base) | New project Steels from Russia | Raache steels from Finland | Raache steels large plates | Combine st. Russ + Fin |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Hull weight (t) | 2127 -100% | 100 % | 102 % | 102 % | 101,5 % |
| Steel for repair (t) | 2096 - 100% | 96,5 | 77,5 | 75,5 | 77,5 |
| Summary weight (t) | 4223 - 100% | 98 | 90 | 88 | 89,5 |
| Cost of hull building (th.$) | 1128,5 - 100% | 102,5 | 139,5 | 140 | 120,5 |
| Cost of hull repair (th.$) | 1395 - 100% | 80,5 | 82 | 79,5 | 73 |
| Summary investment (th.$) | 2523 - 100% | 90,5 | 108 | 106 | 94 |
| Labor for build (th.hours) | 333 - 100% | 100 | 101,5 | 101,5 | 101 |
| Labor for repair (th.hours) | 509 - 100% | 63,5 | 47,5 | 46,5 | 47,5 |
| Dock time | - 100% | 63 | 47,5 | 46,5 | 48 |
| Total investment for 25 years | - 100% | 67 | 55,4 | 54,5 | 53,5 |

Note:
Steel plates: "Sakhalin - 1" was made of Russian steels grade 09G2 and
10G2S1D ( RS D32S and RS D40S)
New project : var. 2 - Russian steels D32 and D40
var. 3 - Finnish steels from Raache:
RAEX 32E Polar, RAEX 36E Polar, NV D27
var.4 - Finnish steels (var.3 ) large size.
var.5 - Optimal distributed Finnish and Russian steels
Base plate sizes (mm) 2000x7000 , 2400x7500 - all together 420 plates
Large plate sizes (mm) 2500x12250 , 3000x12750 - all together 206 plates

The criterion of solution efficiency is taken as a sum of manufacturing cost and cost related to ship repair dock time during the complete life cycle far all components used for calculations (Fig. 7). A comparison of some solution variants regarding steel selection and distribution in the hull of "Sakhalin" type ferries is given in Tables 1-2.

Nowadays all calculations are carried out with the help of special system called "OPTIMAL SHIP HULL DISTRIBUTION SYSTEM" (SD) which presents the results as three-dimensional hull views (Fig. 8).

Designers in offices and steels users at ship building yards have possibility to solve efficiently a broad range of problems related to the selection and delivery of steel during ship development, manufacturing and repair.

*Table 2. Cost and men-hours of welding work for ferry plating calculated with the help of the graph model.*

| Type of electrode<br>diameter (mm)<br>Angle, degree | UONI-13/45A<br>4,0<br>60 | OK 50.10<br>4.0<br>60 | OK 50.10<br>3.0<br>60 | OK 48.68<br>4.0<br>60 | E138/50H<br>4.0<br>60 |
|---|---|---|---|---|---|
| Cost of welding work (th.$) | | | | | |
| Hull building. | 50245 - 100% | 100 | 130 | 104 | 97.5 |
| Hull repairing. | 1351 -100% | 100 | 185 | 625 | 33 |
| Labor of welding work (th.$) | | | | | |
| Hull building | 5803 - 100% | 100 | 131 | 102 | 105,5 |
| Hull repairing | 584 - 100% | 100 | 233 | 680 | 33 |

Note: UONI-13/45A -electrode grade according Russian standart,
OK and E138/50H - ESAAB electrodes

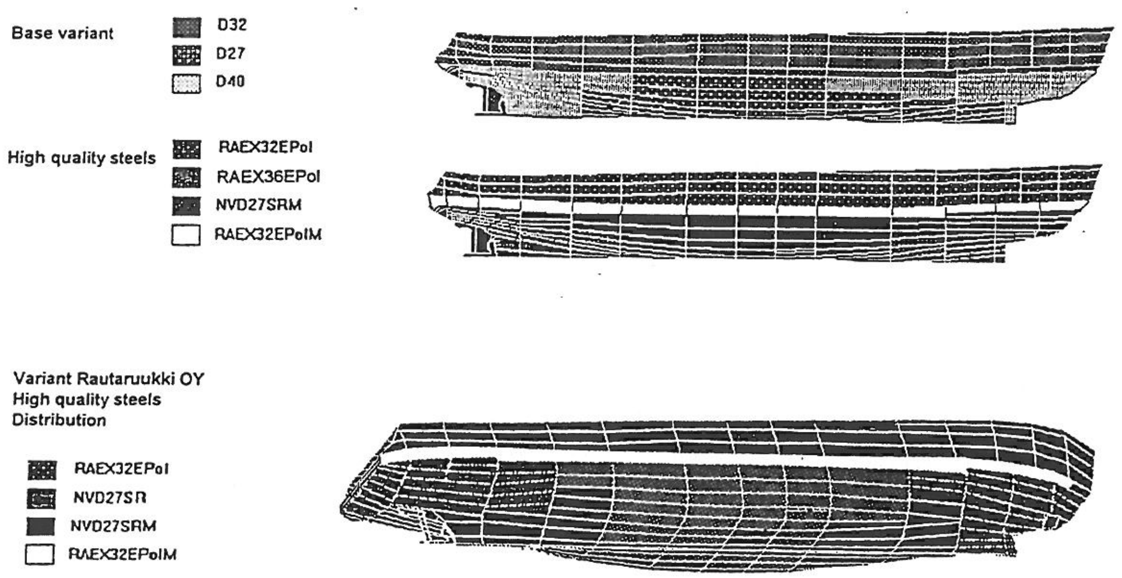

*Fig. 8. Three-dimensional view of the shell plates for the "Sakhalin" ferry with hull made advanced variant of the new generation train-ferry.*

## SUMMARY

The graph model for solving the problem of material distribution throughout a ship's hull yield an individual solution for every component by selecting the conditions of its joint with its neighbours.

A large number of components causes a waste of computer time. A special modification of the Dejikstra algorithm with high numeric capability allows optimal or sub-optimal variants to be found simply without complications.

The effectiveness of the model and of its computer implementation is due to the pointer representation of the graph and the possibility of obtaining sub-optimal solutions. These features help the designer to take the final decision according to circumstances.

The graph model allows decomposition and "zooming" of any part of the system for precise design of selected components of the hull.

When this method is used it is necessary to observe to following rules:

- CR must not be marked out along the block length,
- plates and sections must not be used in one and same CR,
- it is recommended to unite groups of details on the basis of their functions: decks, freeboard, ice strake, bottom, inner bottom, etc.,
- it is necessary to mark out: sheer strake, deck stringer, bilge strake, keel strake, ice strengthening elements, cargo hold comings,
- it is recommended to separate sides and flanges of welded sections as potentially possible details to be manufactured from different steels,
- small details lightly affecting hull weight and its repair can be assigned to nearby CRs,
- each plate or detail located in areas of intensive corrosion wear must be included in a separate CR.

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