Combinatorial Methods for of Rational Ship-construction Design

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Abstract. The study results on the development of computer-based design methodology for rational operational model of building a ship hull on the stocks are presented in the paper. The formalization of technological restrictions regulating the procedure for assembling the hull has been carried out. The task of choosing the optimal (rational), according to the selected criterion, variant for the execution of work on assembling the hull was solved taking into account the existing technological and institutional limitations. The developed methodology is based on the methods proposed by the authors and relevant for shipbuilding, displaying the set of possible work sequence variants, using search optimization methods to solve select problems and, in particular, the modified branch-and-bound method, as well as probabilistic searches. The article presents some results of the "set" testing in terms of the "duration of construction". The prospects for digitalizing the process of desired model development using the proposed methodology, as well as the economic consequences of introducing the results into production, are estimated.

1. Introduction
Management in any organizational and technological system is associated with the sequential implementation of three functions: planning, cost accounting and adjustment. The implementation of these functions is repeated cyclically during the ship construction, which can be described as a "sliding" control.

Network planning and control methods have been actively used in shipbuilding since the middle of the 20th century, significantly improving the quality of management and reducing the entropy (measure of chaos) of ship building processes [1, 2]. Concurrently, the functionality and complexity of ships is constantly growing, moreover, shipbuilding integrates the activities of many economic structures that operate with very large and varied resources. In these conditions, the responsibility for making, if not optimal, then at least rational, decisions increases. The paper sets out an approach on addressing the digitalization task of model development that underlies managerial decision-making in shipbuilding.

2. Relevance
A set of tied activities with metrics is the basis for model development. Activities can be carried out in a certain sequence, which is determined by the hull assembly technology and is limited by the forecasted external and internal production conditions of the ship construction. At the same time, the staging activity simulation becomes the basis for the activity schedule for other types of work
performed during the ship construction (assemble-welding, hull plating and other types of production).

From the point of view of the modeling subject, this model (hereinafter used) can be considered normative, developed on the basis of current ideas about the future. The problem is that such a model cannot be considered either optimal or even rational.

The main competitive advantage of a shipbuilding enterprise is the price (cost) of its products. The ship cost price varies significantly depending on the duration of its construction. Thus, the change in cost can reach 20-30% due to a change in the assembly order of the ship's hull. The model is formed under uncertainty, which is figuratively "square-law" of the simulated period. If we add subjectivity (that exists when building a model) to this, it can be argued that the main weakness of control systems is closely related to the currently accepted methods for constructing (designing) models, i.e. building of models. Despite the abundance of literature on network management methods, precious few studies are devoted to the actual technology of model development. This is not strange, since building a detailed network model is a long and laborious process of intellectual coordination between large amount of activities, which is difficult to formalize, and therefore, to digitalize.

3. Research objective
Choose the optimal (rational) model according to the selected criterion from the set of technologically and institutionally acceptable variants for hull assembly activities.

A well-known fact is that in the real conditions of the production process the same ship-building activity can be performed in different sequences. Displaying workflow variants by graph theory methods leads to a significant number of network models. Manual construction of all possible network models for building a ship is practically impossible [3].

There is currently no methodology on the on-line model design for the workflow rational organization that takes into account the combinatorics of the process, which a priori reduces the quality of managerial decision-making and the economic efficiency of production.

4. The methodology of model design for rational work activity management
Technological features of shipbuilding necessitated the creation of organizational and technological rules for the formation of many variants for the hull production. The Department of Shipbuilding Production Management of St.Petersburg State Maritime Technical University has consolidated two tasks:
   A. To isolate from the set of spatially possible variants for assembling a block from sections of the set of technologically feasible variants \( \{T\} \).
   B. To isolate the sets of variants admissible by the prevailing (situational) production conditions \( \{R\} \) from the set of technologically feasible variants \( \{T\} \).

The presentation of technological limitations regulating the hull assembling activities was formalized to solve Task A. Databases were developed containing data on the spatial relationships of structures, technological and temporal conditioning, labor information, etc. This data was presented as a relational database [4].

Figure 1 presents a truncated tree structure’s fragment of possible assembly sequences of sections included in the hypothetical ship block. The number sequence of graph nodes lying on the path from the root of the tree to the last branch level is one of the possible assembly sequences.

The practice of using the method of describing the set makes it possible to draw the following conclusions:
   1. The tree structure describes any combination of sections (structures), united by technological links. A path in a tree structure is the sequence variants of structural assembly.
   2. Each element of the set (sequence variant of Fig. 1) is technologically feasible. The formed set is the basis for topological layouts of workflow models. Each element of this set has its own economic prospects.
The “curse of dimensionality” that accompanies emerging practical problems has led to the creation of a family of search optimization methods [5, 6, 7]. In this study, the choice of the branch and bound method for solving Task B was substantiated:

1. Divide the set of possible variants of problem solutions into a family of subsets, each having additional specific properties. For each subset of elements, as specific properties, an estimate of the possible value of the criterial indicator $\tau(r)$ is calculated. The methods for calculating this estimate are determined by industry specifics of the problem being solved.

2. Use these specific properties in search for logical contradictions in the description of individual subsets. The condition for truncating subsets is introduced:

$$ T_0 < \tau(r_m) , $$

where $T_0$ is the minimum value of the desired parameter (duration) found by the current moment of calculation.

3. Omit from consideration the subjects whose description is logically contradictory (1) [8].

In practical terms, it was necessary to provide a solution to problems of significant dimension, and therefore, an author's modification of the branch and bound method was proposed, as well as statistical search methods. This required adjusting the problem statement. The goal was to use the existing freedom in finding the sequence of assembly sections to select a sequence on the basis of which a rational option for the duration of work can be built:

$$ T(r^*) - T(r^r) < \varepsilon , $$
where: $T(r')$ is the rational (best) value of the "duration" indicator in the generated sample, and $\varepsilon$ is the value determined as a result of assessing the necessary (from a practical point of view) accuracy of the problem solution.

The formation of a random variant occurs moving along a tree from the root to the last level (Fig. 1), while the movement direction along tree structure of the set is selected in a pseudo-random way.

Studies conducted using a program implementing the Monte Carlo method have led to the conclusions coinciding with the conclusions made in [9], namely, that the criteria distribution function of randomly generated models is asymptotically normal for systems with a large number of activities.

The variable pattern “duration” histogram is shown as an illustration in Figure 2, constructed according to the results of test sequence conducted using data on the block of one of the ships.

![Figure 2. Model sample histogram by "duration" (in shifts).](image)

It is necessary to assess whether the obtained samples belong to one or another distribution law in order to assess the rationality of the best test sequence result. A fairly reliable membership estimate of sampling distributions is usually obtained by the maximum likelihood method [10]. The named method makes it possible to select the "best" distribution law and to evaluate the proximity of the main entity estimates to actual data.

According to the maximum likelihood method, the likelihood indicator of the observed values $\zeta$ was determined from the parameters of the sampling distribution and the distribution law was chosen for which the $\zeta$ indicator turns out to be the largest in magnitude. As the distribution law characterizing the general set of block assembling cycle durations, the normal law was chosen, where $T = 0.01$ and $\varepsilon = 0.05$ [11].

From a practical point of view, the $T_{r'p}$ itself (a hypothetically optimal value), which corresponds to the lower boundary of interval $3\sigma$, and the solution accuracy index $\alpha$ are important for assessing possible economic consequences. Due to this, it is possible to assess the rationality of the actually obtained result by its deviation from the hypothetical optimum.

The interval $3\sigma$ is determined from the condition that the existence probability of the best decisions in the interval $3\sigma$ is not less than 0.9973.
The error probability (deviation of the found “best” from a hypothetical optimum) did not exceed 1-2% and depended on the dimension of the problem and the sampling size. The accuracy indicator for solving the problem was defined as the ratio

$$\alpha = \frac{T_{ran}-T_{opt}}{T_{opt}} \times 100\%$$,  \hspace{1cm} (3)

where $$T_{opt} = m(T) - 3\sigma$$.

The obtained values of $$\alpha$$ allow, if necessary, to build the dependence of solution accuracy on the statistical sampling size, that is, to solve the practical "sample size - acceptable accuracy" problem.

Table 1 presents the results making possible to state the practical effectiveness of the proposed methods.

| Ship block NO. | Activity duration in the sequence adopted by the enterprise (in shifts) | Optimization results |
|---------------|---------------------------------------------------------------|-----------------------|
| Block 4, N    | 102                                                           | 92                    |
| Block 1, N    | 84                                                            | 76                    |

As you can see, the activity duration, corresponding to the models obtained by the authors, significantly differs from the activity duration carried out in accordance with the models adopted at the enterprise. However, the duration of each individual activity in the compared models is the same. This means that a toolkit has been created offering a way to significantly reduce the ship construction cycle and partially solve the national economic problem on the optimal use of the gigantic financial and material resources integrated into shipbuilding, only by means of permissible changes in the activity order.

5. Scientific novelty and main conclusions

1. The introduction of such techniques, organizing documents and software products will serve as a real digitalization of shipbuilding production managerial processes. The authors identified the main institutional, technological and production constraints regulating the sequence of staging activities. The model development rules on carrying out work in the hull building industry of a shipbuilding enterprise are formalized.

2. Methods of isolating from a set of currently acceptable variants of a “rational” sequence are developed. In the view of authors, the research complex forms a methodology for modeling a private production process in shipbuilding, which determines the activities of all contractors involved in ship building, and therefore the effectiveness of building a specific order (ship). This method can significantly increase the shipbuilding managerial efficiency, as well as the digitalization level, allowing obtaining real-time result, namely, a model that can be called adequate and rational for some period.

3. The experience of adapting the algorithm and mathematical software to real production conditions makes it possible to state the algorithm effectiveness, which is expressed in the significant reduction in predicted cycle duration and entropy level of production system.

4. The introduction of the proposed toolkit can increase the economic efficiency of the shipbuilding production system by accelerating working capital turnover, early commissioning of orders, reducing ship building cost and increasing system competitiveness as a whole.

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