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# Methodology for Shipyard Production Areas Optimal Layout Design

Original scientific paper

A novel methodology for creating a preliminary optimal layout design of shipyard production areas is proposed in this article. Proposed methodology is based on the implementation of a specifically defined procedure in four phases. The first phase established the closeness relationships of the chosen production areas from the shipbuilding process technological point of view, based upon a survey of relevant experts. Thereupon, the second phase proposed the generation and evaluation of all possible production layout variants within the shipyard. The method of systematic layout planning based on previously established closeness relationships was used. Furthermore, after establishing a representative number of most competitive variants, the third phase considered hierarchical modelling, by using the analytical hierarchy process, to choose the variant which most optimally satisfies all criteria. In the fourth and final phase, a sensitivity analysis was performed in order to check the stability of the chosen layout of production areas. The proposed methodology was verified on the example of a real shipyard's layout design optimisation.

**Key words:** *hierarchical modelling, layout design, sensitivity analysis, shipyard, systematic layout planning*

### Metodologija za projektiranje optimalnog rasporeda proizvodnih površina brodogradilišta

Izvorni znanstveni rad

U radu je predložena metodologija za projektiranje optimalnog rasporeda proizvodnih površina brodogradilišta u preliminarnoj fazi. Predložena metodologija se temelji na provođenju točno definirane procedure u četiri faze. U prvoj fazi utvrđeni su odnosi bliskosti odabranih proizvodnih površina sa stajališta tehnologičnosti brodograđevnog procesa, na temelju provedenog anketiranja relevantnih stručnjaka. Zatim se, u drugoj fazi predlaže generiranje te procjena svih mogućih varijanti rasporeda odabranih proizvodnih površina u okvire brodogradilišta. Za tu svrhu primijenjena je metoda sistematskog planiranja rasporeda površina na temelju prethodno utvrđenih odnosa bliskosti. Nadalje, nakon utvrđenog reprezentativnog broja najizglednijih varijanti, u trećoj fazi se među tim varijantama hijerarhijskim modeliranjem, za koje se koristi metoda analitičkog hijerarhijskog procesa, obavlja izbor one koja optimalno udovoljava svim postavljenim kriterijima. U zadnjoj, četvrtoj fazi radi se analiza osjetljivosti kako bi se ispitala stabilnost odabranog rješenja rasporeda proizvodnih površina. Predložena metodologija provjerena je na realnom problemu optimizacije rasporeda proizvodnih površina brodogradilišta.

**Ključne riječi:** *analiza osjetljivosti, brodogradilište, hijerarhijsko modeliranje, projektiranje rasporeda površina, sistematsko planiranje rasporeda površina*

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## 1 Introduction

The need for continuous technological improvement of shipyard production processes, with a goal of achieving a concurrent shipyard, requires a very complex decision making process. For that matter, a large number of different requirements and constraint has to be analysed and valorised in order to be able to find at least an acceptable solution. Moreover, finding the optimal solution requires additional analysis and the use of appropriate scientific methods.

However, expanding of shipyard space and technological improvement could be often conditioned by various objective constraints. For example: terrain characteristics and bounds, closeness of other industries or urban settlements, different domestic and EU law regulations, etc. Therefore, improvement of shipyard production processes often means conducting improvement only within the shipyard boundaries.

Within the presented research, the authors have perceived the lack of proper methodology for design, improvement and optimisation of shipyard production areas layout and corresponding material flow. In the current practice, shipyard management is often using a benchmarking method or automated tools, which usually do not result with optimal design solutions.

Therefore, the authors conducted this research with a goal of establishing a new scientifically based methodology which would enable finding an optimal production areas layout, in efficient and fast manner, with respect to defined constraints. Furthermore, the authors exerted a special effort to make this methodology easily applicable by shipyard management, for whom this methodology is primarily intended.

## 2 Characteristics of shipyard production areas layout design

Generally, the production areas layout design process is geared towards seeking optimal solutions for different activities with corresponding components. This process implies the finding of spatial arrangement of such activities in a given space, satisfying given preferences and constraints [1], [2]. More specifically, it is a complex and subjective problem which includes evolving task dynamics, inadequate information availability, as well as uncertain and conflicting preferences [3], [4].

It is obvious that production areas layout design process is based on designer's creativity and interaction between results of different contradictory disciplines [5]. It is a known fact that majority of software and computerized techniques for layout design ignore creativity and talent of a designer who understands complex interaction between production flow and production areas [6]. Still, there is an approach which includes expert knowledge for decision making and modelling such uncertain problems [7]. It is possible to apply such expert system approach for designing shipyard production area layout.

Production areas in shipbuilding represent an especially interesting problem due to specific characteristics of the shipbuilding production process which involves large scale products requiring wide production areas. The need for investigating such a specific problem arises from a few basic reasons:

I. Size and shape of the existing shipyards areas are often unchangeable because a shipyard is bounded by the sea from one side, and by urban settlements and/or industrial facilities, from the other side.

II. Layout of the existing shipyard facilities is not usually subject to changes due to large scale structures and already established related infrastructure.

III. Evolution of shipbuilding technology procedures imposes different demands and requirements on the production areas in shipyards. Such demands are difficult to implement because of the already specified constraints and limitations.

Due to the mentioned reasons, technological modernisation within the existing shipyards has to be oriented to improving efficiency of using the existing production areas. Therefore, the authors think that within the future development of shipbuilding technology one of the primary goals will be the optimisation of production areas layout.

## 3 Proposed methodology for shipyard production areas layout design

New methodology for designing shipyard production areas layout is based on conducting four phases with a goal to reach an optimal design solution. Such design solution is the basis for further production flow analysis and detailed definitions.

In this article the methodology is applied and verified for designing an optimal production areas layout within the project of technological modernisation of an existing shipyard. The procedure, methods and techniques of developed methodology are explained in this section. Furthermore, proposed methodology pattern of procedure is shown in Figure 1.

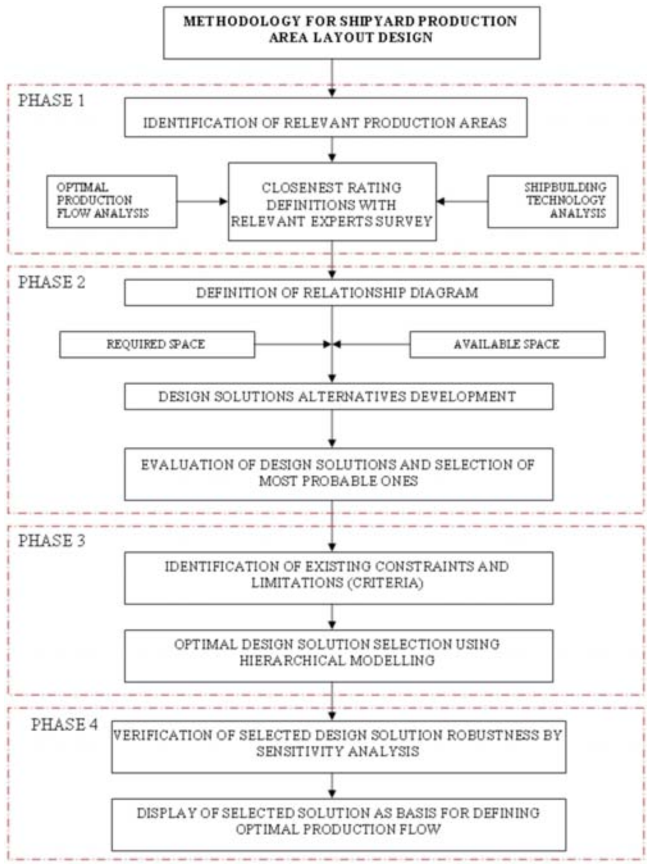


Figure 1 **Proposed methodology Pattern of Procedures**
Slika 1 **Blok dijagram predložene metodologije**

### 3.1 PHASE 1 – Identification of closeness ratings of selected shipyard production areas using expert survey method

Within the first phase of the developed methodology the production areas that are directly participating in the basic shipyard production process are selected. Selected production areas are given a number and presented in Figure 2 on the example of one modern 5th technology level shipyard of *Group E* [8].

A combination of these selected production areas directly changes the basic production flow and therefore influences the shipyard production process. In that content it is necessarily to identify closeness ratings with corresponding weight factors for such areas. In this paper closeness ratings are described with numbers between 0 and 5, and letters *A, E, I, O, U* and *X* to be input data for phase 2, Table 1.


Figure 2 **Basic shipyard production areas**
Slika 2 **Osnovne brodograđevne proizvodne površine**

Legend: 1. Steel stockyard; 2. Plate cutting and forming; 3. Profile cutting and forming; 4. Plate cutting; 5. Panel line; 6. Subassembly; 7. Section blasting and painting; 8. Pipe cutting, forming and outfitting; 9. Locksmith and craft workshop 10. Outfitting quay with workshops; 11. Equipment blasting and painting; 12. Area for section assembling and finalizing; 13. Area for section finalizing; 14. Berth; 15.Sea.

Table 1 **Closeness ratings**
Tablica 1 **Pokazatelji odnosa bliskosti**

| Number code | Closeness | Letter code |
|---|---|---|
| 5 | Absolutely necessary | A |
| 4 | Especially important | E |
| 3 | Important | I |
| 2 | Ordinary | O |
| 1 | Unimportant | U |
| 0 | Not desirable | X |

Those closeness ratings between selected production areas are defined considering knowledge of optimal production flow and using survey method among a large number of relevant experts from shipyards as well as from universities. With the same survey method weight factors were also defined.

Based on gathered information within the survey, closeness ratings are calculated using the following relation:

$$w_i = \frac{\sum_{k=1}^{m} r_{jk}}{m} \qquad (1)$$

where:
$w_i$ - weight factor for *i-th* closeness,
$r_{jk}$ - closeness rating for *i-th* closeness form *k-th* expert,
$m$ - number of experts.

Using such data, the design solutions which are favourable regarding material flow will be highly scored using Systematic Layout Planning (SLP) score system [9]. Closeness ratings of selected production areas are presented within relationship matrix as shown in Table 2.

Table 2 **Relationship matrix**
Tablica 2 **Matrica odnosa bliskosti**

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *SKL* | *ROL* | *ROP* | *RRL* | *PAN* | *RPM* | *ZIB* | *RIC* | *BIL* | *MOT* | *ZBO* | *OD1* | *OD2* | *NAV* | *SEA* |
| **1** | *SKL* | ◇ | *A* | *A* | *A* | *O* | *O* | *U* | *E* | *O* | *O* | *O* | *U* | *U* | *U* | *I* |
| **2** | *ROL* | *A* | ◇ | *I* | *I* | *I* | *E* | *U* | *U* | *U* | *U* | *U* | *O* | *U* | *O* | *U* |
| **3** | *ROP* | *A* | *I* | ◇ | *I* | *E* | *E* | *U* | *U* | *O* | *U* | *U* | *O* | *U* | *U* | *U* |
| **4** | *RRL* | *A* | *I* | *I* | ◇ | *A* | *E* | *U* | *U* | *O* | *U* | *U* | *O* | *U* | *O* | *U* |
| **5** | *PAN* | *O* | *I* | *E* | *A* | ◇ | *A* | *I* | *U* | *O* | *U* | *U* | *I* | *O* | *O* | *U* |
| **6** | *RPM* | *O* | *E* | *E* | *E* | *A* | ◇ | *A* | *I* | *I* | *I* | *O* | *E* | *E* | *I* | *O* |
| **7** | *ZIB* | *U* | *U* | *U* | *U* | *I* | *A* | ◇ | *U* | *U* | *O* | *O* | *E* | *E* | *E* | *U* |
| **8** | *RIC* | *E* | *U* | *U* | *U* | *U* | *I* | *U* | ◇ | *I* | *E* | *E* | *I* | *I* | *I* | *I* |
| **9** | *BIL* | *O* | *U* | *O* | *O* | *O* | *I* | *U* | *I* | ◇ | *E* | *E* | *I* | *O* | *I* | *O* |
| **10** | *MOT* | *O* | *U* | *U* | *U* | *U* | *I* | *O* | *E* | *E* | ◇ | *I* | *I* | *O* | *I* | *E* |
| **11** | *ZBO* | *O* | *U* | *U* | *U* | *U* | *O* | *O* | *E* | *E* | *I* | ◇ | *I* | *I* | *I* | *U* |
| **12** | *OD1* | *U* | *O* | *I* | *O* | *I* | *E* | *E* | *I* | *I* | *I* | *I* | ◇ | *I* | *A* | *O* |
| **13** | *OD2* | *U* | *U* | *U* | *U* | *O* | *E* | *E* | *I* | *O* | *O* | *I* | *I* | ◇ | *E* | *O* |
| **14** | *NAV* | *U* | *O* | *U* | *O* | *O* | *I* | *E* | *I* | *I* | *I* | *I* | *A* | *E* | ◇ | *A* |
| **15** | *SEA* | *I* | *U* | *U* | *U* | *U* | *O* | *U* | *I* | *O* | *E* | *U* | *O* | *O* | *A* | ◇ |

Weight factors of corresponding closeness ratings are presented in Table 3.

Table 3 **Closeness weight factors**
Tablica 3 **Težinski faktori oznaka bliskosti**

| Closeness Letter code | Weight factor, $w_i$ |
|---|---|
| *A* | *45* |
| *E* | *11* |
| *I* | *3* |
| *O* | *1* |
| *U* | *0* |
| *X* | *-45* |

Using the data shown in Table 2 and 3, within the next phase all possible design solutions can be analysed regarding optimal production flow using SLP method.

### 3.2 PHASE 2 – Generation of all possible design solutions of selected production areas by using SLP method

A brief review of the SLP procedure is shown in Figure 3 [10]. The SLP begins with PQRST analysis (step 1) for the overall production activities. The data collection fields including P (product), Q (quantity), R (routing), S (supporting), and T (time) should be scrutinized in order to assure the validness of the input data at the design stage.

In the flow of materials analysis (step 2), all material flows from the whole production line are aggregated into a from-to chart that represents the flow intensity among different tool sets or work positions. The step of “activity relationships” (step 3) performs qualitative analysis towards the closeness relationship decision among different work positions.

The step of “relationship diagram” (step 4) positions areas spatially. For those work positions (areas) that have strong interactions and/or closeness relationships are placed in proximity.

The steps of “space requirements” and “space available” (steps 5 and 6) determine the amount of floor space to be allocated to each work position. This decision is particularly critical to a workshop design problem due to the costly clean room floor space and the difficulty in future expansion.

The step of “space relationship diagram” (step 7) adds area size information into the relationship diagram from step 4. Additional design constraints and limitations are considered before the start of block layout generation in steps 8 and 9. Step 10 then develops layout alternatives as design candidates. Step 11 chooses the final design from these design candidates.

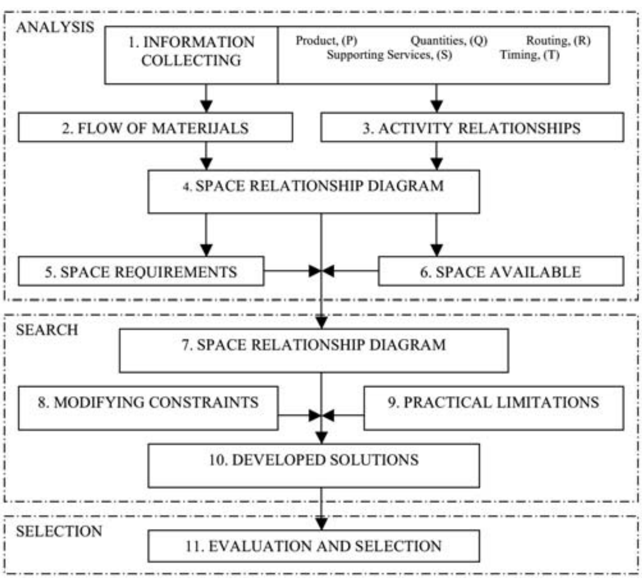


Figure 3 **SLP procedure**
Slika 3 **SLP procedura**

Generally, every shipyards layout includes:

1) Relationship between selected shipyard production areas,

2) Size and shape of particular production area,

3) Spatial arrangement of production areas within shipyard layout.

Within the second phase of proposed methodology, using the SLP method and taking into consideration these elements, the goal is procedurally obtained. For faster generation of the results the specialised software was used [11].

The goal of this phase is selection of the most feasible production areas layouts analysing all the possible combinations of shipyard production areas. There is a very large number of such combinations, for example, for 20 production areas there is 2.4 x $10^{18}$ possible combinations.

All generated layouts as design solutions are evaluated by SLP score, calculated according to closeness criteria as follows:

$$s = \sum_{i=1}^{n_p} w_i \cdot Y_i \tag{2}$$

where:
$Y_i$ - number of closeness of $i$-class,
$w_i$ - weight factor for $i$-closeness,
$s$ - SLP score,
$n_p$ - number of production areas.

A larger SLP score number within particular layout solution means that it is closer to satisfy optimal production flow. The highest possible of normalised SLP score numbers is one. One of the generated layouts will certainly be the best regarding the SLP score, however, it is not necessarily an optimal solution regarding shipyard requirements. Namely, besides the requirements for optimal production flow, other important requirements and constraints have to be taken in consideration. For example, financial limitations, existing infrastructure which cannot be changed, need for maintaining ongoing production etc, are the constraints that cannot be included within this phase.

Therefore, within this phase the authors selected 20 best design alternatives regarding the SLP score, because this is the sample where the design solution which optimally meats all constraints and limitations is most likely expected.

This phase was conducted over the real shipyard project using specialised software BlockPlan for Windows 1.4 and the results are shown in Figure 4.

### 3.3 PHASE 3 – Hierarchical modelling with AHP method for optimal design solution selection

In the third phase of the proposed methodology, for optimal design solution selection, authors suggest using Analytical Hierarchy Process (AHP) [12]. The AHP method as one of multi-attribute decision making approaches. It is a structured technique for dealing with complex decisions. Rather than prescribing a “correct” decision, the AHP helps the decision makers find the one that best suits given constraints and limitations (criteria). Based on mathematics and psychology, it was developed by Thomas L. Saaty.

So, in order to select the optimal design between previously selected 20 probable solutions it is necessary to identify relevant constraints and limitations which this design has to satisfy optimally. The criteria resulted from design requirements and shipyard’s spatial and technological limitations, and they are as follows:

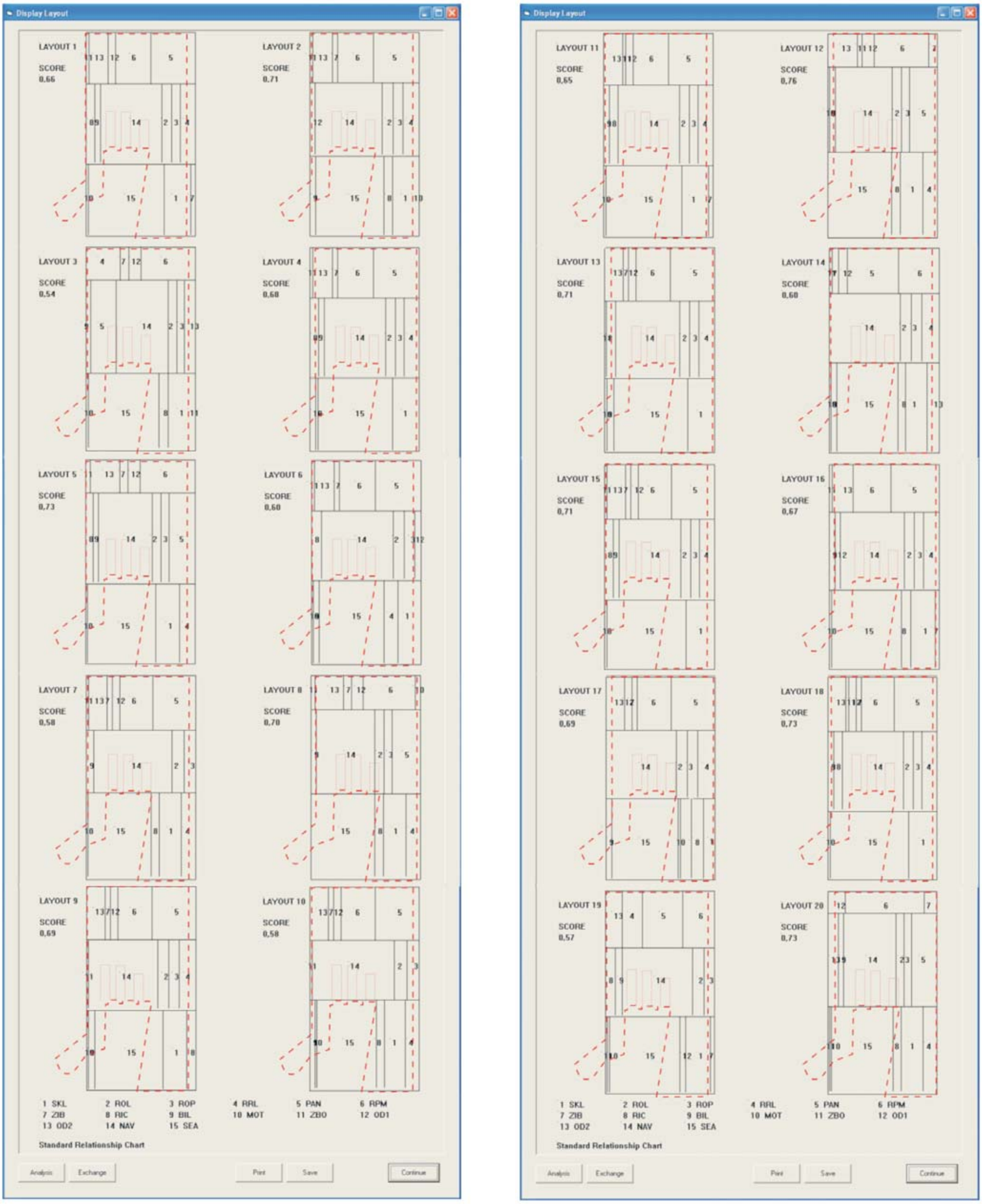

Figure 4 **The best 20 generated design solutions regarding SLP score**
Slika 4 **20 najboljih varijanti projektnog rješenja temeljem SLP ocjene**

- Criterion 1: SLP score,
- Criterion 2: Investment costs,
- Criterion 3: Maintaining existing facilities as much as possible,
- Criterion 4: Feasibility by taking in consideration ongoing production process,
- Criterion 5: Retaining the shipyard's existing boundaries.

Detailed analysis of these 20 design solutions regarding the selected criteria was performed and the results are shown in Table 4.

Table 4 **Basic characteristics of the selected design solutions regarding given criteria**
Tablica 4 **Osnovne značajke alternativa prema postavljenim kriterijima**

| CRITERIA / DESIGN SOLUTION | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| | | *SLP score* | *Investment costs, k€* | *Number of existing facilities which have to be demolished* | *Obstruction of ongoing production process, %* | *Need for expanding outside of the shipyard* |
| 1 | *Solution 1* | 0.66 | 24299 | 14 | 40 | No |
| 2 | *Solution 2* | 0.71 | 21154 | 7 | 15 | No |
| 3 | *Solution 3* | 0.54 | 24182 | 11 | 55 | No |
| 4 | *Solution 4* | 0.68 | 24794 | 14 | 35 | No |
| 5 | *Solution 5* | 0.73 | 24812 | 15 | 30 | Yes |
| 6 | *Solution 6* | 0.6 | 24722 | 13 | 50 | No |
| 7 | *Solution 7* | 0.58 | 23947 | 10 | 25 | No |
| 8 | *Solution 8* | 0.7 | 25727 | 8 | 25 | Yes |
| 9 | *Solution 9* | 0.69 | 24959 | 11 | 40 | Yes |
| 10 | *Solution 10* | 0.58 | 24317 | 11 | 40 | No |
| 11 | *Solution 11* | 0.65 | 24859 | 14 | 30 | No |
| 12 | *Solution 12* | 0.76 | 26177 | 11 | 30 | Yes |
| 13 | *Solution 13* | 0.71 | 24709 | 14 | 50 | No |
| 14 | *Solution 14* | 0.6 | 25709 | 12 | 40 | No |
| 15 | *Solution 15* | 0.71 | 24659 | 14 | 40 | No |
| 16 | *Solution 16* | 0.67 | 24609 | 11 | 55 | No |
| 17 | *Solution 17* | 0.69 | 20974 | 6 | 10 | No |
| 18 | *Solution 18* | 0.73 | 24544 | 12 | 30 | No |
| 19 | *Solution 19* | 0.57 | 27797 | 13 | 90 | No |
| 20 | *Solution 20* | 0.73 | 25497 | 13 | 25 | Yes |

These criteria are included in hierarchical model development and based on them an optimal solution, as the method goal, will be found among the chosen design solutions.

Hierarchical model structurally consists of the following levels: a goal, criteria, sub-criteria and alternatives (solutions), Figure 5.

The goal is placed on the highest hierarchical level and it is not compared to any other element of the hierarchical structure. On the first level there are $k$ criteria which are compared to each other in pairs regarding the directly superior element - goal. The $k \cdot (k - 1)/2$ of comparisons is required. The same procedure is repeated for the next hierarchical level, all the way down to the last $r$ level, until all comparisons of all solutions with respect to the superior criteria, down to *r-1* level, is completed.

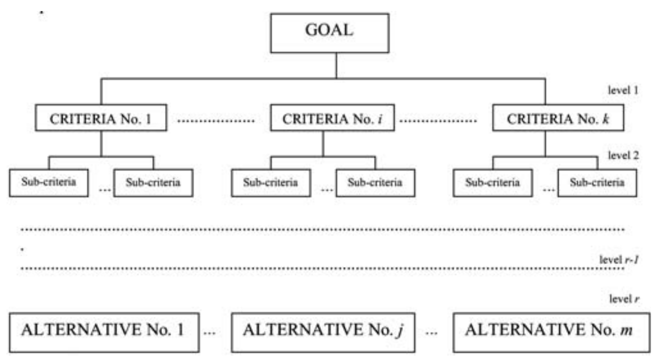


Figure 5 **AHP hierarchical model**
Slika 5 **AHP hijerarhijski model**

Each comparison of two elements of the hierarchical model is done by Saaty's scale of relative importance as shown in Table 5.

Table 5 **Saaty's scale of relative importance**
Tablica 5 **Saaty-jeva ljestvica vrednovanja**

| **Intensity of relative importance** | **Definition** | **Explanation** |
|---|---|---|
| 1 | Equal importance | Two activities contribute equally to the objective |
| 3 | Moderate importance of one over another | Experience and judgment slightly favour one activity over another |
| 5 | Essential or strong | Experience and judgment strongly favour one activity over another |
| 7 | Very strong importance | An activity is strongly favoured and its dominance is demonstrated in practice |
| 9 | Extreme importance | The evidence favouring one activity over another is of the highest possible order of affirmation |
| 2,4,6,8 | Intermediate values between two adjacent judgments | When compromise is needed between two judgments |

The results of elements comparison on the observed hierarchical level are organised in matrix form as follows:

If $n$ elements are compared to each other with respect to the superior corresponding element on a higher hierarchical level, then, when comparing $i$ element to $j$ element using Saaty's scale of relative importance, numerical coefficient $a_{ij}$ is determined and placed in its adequate position in matrix $A$:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdot & \cdot & a_{1n} \\ a_{21} & a_{22} & \cdot & \cdot & a_{2n} \\ \cdot & \cdot & & & \cdot \\ \cdot & \cdot & & & \cdot \\ a_{n1} & a_{n2} & \cdot & \cdot & a_{nn} \end{bmatrix} \tag{3}$$

Inverse result value is placed on position $a_{ji}$ as to maintain consistency of decision making. Detailed description of AHP method can be found in [13].

Within this research specialised software for hierarchical modelling has been developed and particularly adapted for the use in shipyard production area layout design. Within this software the AHP method is used for finding relevant results organised as a ranking list of selected design alternatives. With AHP method local priorities are found, as shown in Figure 6, and based on them overall priorities of design solutions are calculated using equation (4).

| | WEIGHT CRITERIA RATIO | K1 | K2 | K3 | K4 | K5 | |
|---|---|---|---|---|---|---|---|
| | LOCAL PRIORITIES OF ALTERNATIVES OVER PARTICULAR CRITERIA | CRITERIA 1 | CRITERIA 2 | CRITERIA 3 | CRITERIA 4 | CRITERIAJ 5 | OVERALL PRIORITIES |
| ALTERNATIVES | SOLUTION 1 | $A_{1\text{-}1}$ | $A_{2\text{-}1}$ | $A_{3\text{-}1}$ | $A_{4\text{-}1}$ | $A_{5\text{-}1}$ | $P_1$ |
| | SOLUTION 2 | $A_{1\text{-}2}$ | $A_{2\text{-}2}$ | $A_{3\text{-}2}$ | $A_{4\text{-}2}$ | $A_{5\text{-}2}$ | $P_2$ |
| | SOLUTION 3 | $A_{1\text{-}3}$ | $A_{2\text{-}3}$ | $A_{3\text{-}3}$ | $A_{4\text{-}3}$ | $A_{5\text{-}3}$ | $P_3$ |
| | SOLUTION 4 | $A_{1\text{-}4}$ | $A_{2\text{-}4}$ | $A_{3\text{-}4}$ | $A_{4\text{-}4}$ | $A_{5\text{-}4}$ | $P_4$ |
| | SOLUTION 5 | $A_{1\text{-}5}$ | $A_{2\text{-}5}$ | $A_{3\text{-}5}$ | $A_{4\text{-}5}$ | $A_{5\text{-}5}$ | $P_5$ |
| | SOLUTION 6 | $A_{1\text{-}6}$ | $A_{2\text{-}6}$ | $A_{3\text{-}6}$ | $A_{4\text{-}6}$ | $A_{5\text{-}6}$ | $P_6$ |
| | SOLUTION 7 | $A_{1\text{-}7}$ | $A_{2\text{-}7}$ | $A_{3\text{-}7}$ | $A_{4\text{-}7}$ | $A_{5\text{-}7}$ | $P_7$ |
| | SOLUTION 8 | $A_{1\text{-}8}$ | $A_{2\text{-}8}$ | $A_{3\text{-}8}$ | $A_{4\text{-}8}$ | $A_{5\text{-}8}$ | $P_8$ |
| | SOLUTION 9 | $A_{1\text{-}9}$ | $A_{2\text{-}9}$ | $A_{3\text{-}9}$ | $A_{4\text{-}9}$ | $A_{5\text{-}9}$ | $P_9$ |
| | SOLUTION 10 | $A_{1\text{-}10}$ | $A_{2\text{-}10}$ | $A_{3\text{-}10}$ | $A_{4\text{-}10}$ | $A_{5\text{-}10}$ | $P_{10}$ |
| | SOLUTION 11 | $A_{1\text{-}11}$ | $A_{2\text{-}11}$ | $A_{3\text{-}11}$ | $A_{4\text{-}11}$ | $A_{5\text{-}11}$ | $P_{11}$ |
| | SOLUTION 12 | $A_{1\text{-}12}$ | $A_{2\text{-}12}$ | $A_{3\text{-}12}$ | $A_{4\text{-}12}$ | $A_{5\text{-}12}$ | $P_{12}$ |
| | SOLUTION 13 | $A_{1\text{-}13}$ | $A_{2\text{-}13}$ | $A_{3\text{-}13}$ | $A_{4\text{-}13}$ | $A_{5\text{-}13}$ | $P_{13}$ |
| | SOLUTION 14 | $A_{1\text{-}14}$ | $A_{2\text{-}14}$ | $A_{3\text{-}14}$ | $A_{4\text{-}14}$ | $A_{5\text{-}14}$ | $P_{14}$ |
| | SOLUTION 15 | $A_{1\text{-}15}$ | $A_{2\text{-}15}$ | $A_{3\text{-}15}$ | $A_{4\text{-}15}$ | $A_{5\text{-}15}$ | $P_{15}$ |
| | SOLUTION 16 | $A_{1\text{-}16}$ | $A_{2\text{-}16}$ | $A_{3\text{-}16}$ | $A_{4\text{-}16}$ | $A_{5\text{-}16}$ | $P_{16}$ |
| | SOLUTION 17 | $A_{1\text{-}17}$ | $A_{2\text{-}17}$ | $A_{3\text{-}17}$ | $A_{4\text{-}17}$ | $A_{5\text{-}17}$ | $P_{17}$ |
| | SOLUTION 18 | $A_{1\text{-}18}$ | $A_{2\text{-}18}$ | $A_{3\text{-}18}$ | $A_{4\text{-}18}$ | $A_{5\text{-}18}$ | $P_{18}$ |
| | SOLUTION 19 | $A_{1\text{-}19}$ | $A_{2\text{-}19}$ | $A_{3\text{-}19}$ | $A_{4\text{-}19}$ | $A_{5\text{-}19}$ | $P_{19}$ |
| | SOLUTION 20 | $A_{1\text{-}20}$ | $A_{2\text{-}20}$ | $A_{3\text{-}20}$ | $A_{4\text{-}20}$ | $A_{5\text{-}20}$ | $P_{20}$ |

Figure 6 **Local and overall priorities of design solutions**
Slika 6 **Lokalni i ukupni prioriteti projektnih alternativa**

$$P_i = A_{1-i} \cdot K_1 + A_{2-i} \cdot K_2 + A_{3-i} \cdot K_3 + A_{4-i} \cdot K_4 + A_{5-i} \cdot K_5 \tag{4}$$

Finally, based on determined priorities from $P_1$ to $P_{20}$, the solution with the highest value is selected and such solution is considered to be the optimal one.

### 3.4 PHASE 4 – Stability determination of selected design solution with sensitivity analysis

To conclude if the suggested rank list of design solution is stable, the Sensitivity Analysis (SA) is conducted for various combinations of input data within phase 4. Sensitivity Analysis belongs to Operation Research methods within linear programming and is used for analysing how changes of model parameters are influencing the optimal solution [14].

The purpose and results of SA application are as follows:

- Determination of the stability of optimal design solution,
- Simplification of hierarchical model,
- Determination of new values for parameters of hierarchical model, based on experiments,
- Determination of critical parameters of hierarchical model, etc.

There are two types of SA as follows [15]:

- **Analytical SA:**
  - for well defined systems,
  - solving problem using partial derivation (5),

$$S_x^F = \frac{\partial F}{\partial x}, \tag{5}$$

where $S$ defines sensitivity function (change intensity) of goal function $F$ related to changes of parameter $x$.

- **Empirical SA:**
  - influence of parameter values change on optimal solution is analysed by experiments,
  - Such type of SA is more applicable to complex systems.

Within the proposed methodology the empirical SA is suggested due to the complexity of shipyard production process. For conducting SA within real problem the *Expert Choice* software was used [16]. The following empirical SA types are used:

- Dynamic,
- Performance (Figure 7),
- Gradient,
- Head to Head.

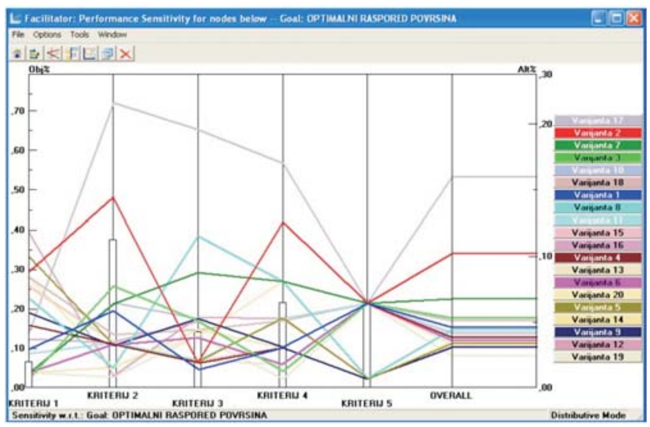


Figure 7 **Results of performance SA**
Slika 7 **Rezultati analize izvedbene osjetljivosti**

Using SA within phase 4, the selected optimal design solution from phase 3 was confirmed as stable and therefore as final solution.

## 4 Presentation of selected design solution

With the proposed methodology, optimal design solution has been selected. This is solution No. 17. This solution is presented

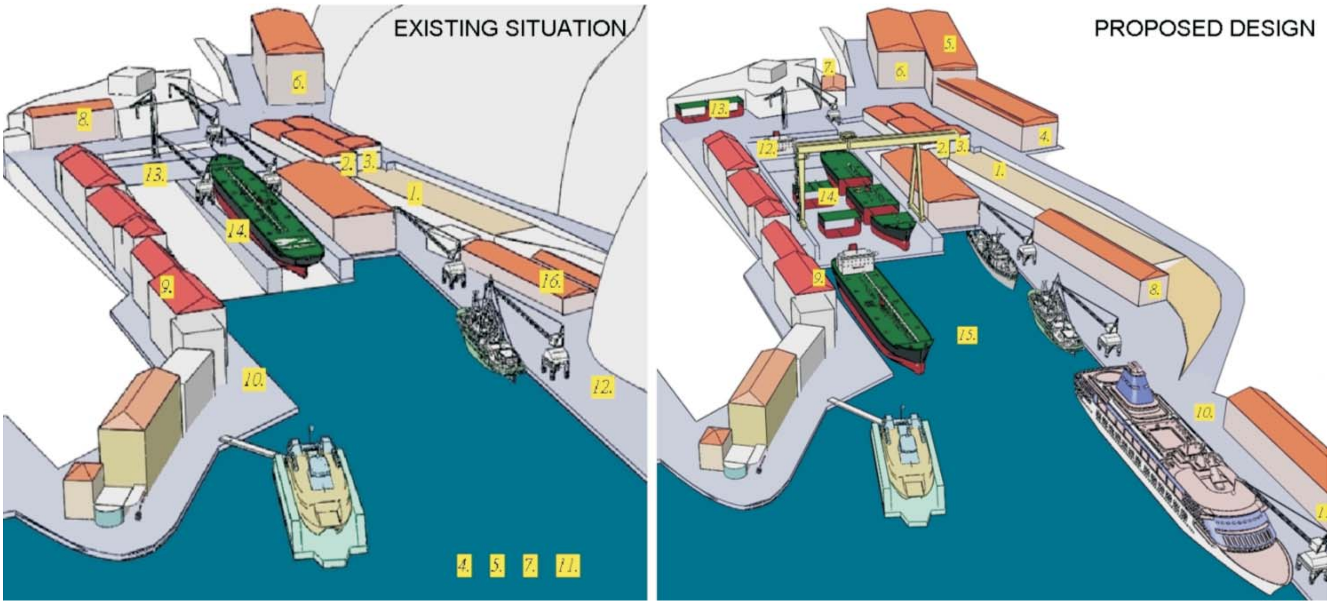


Figure 8 **3D model of existing (left) and proposed optimal design solution (right)**
Slika 8 **3D virtualni prikaz zatečenog stanja (lijevo), te optimalnog projektnog rješenja rasporeda proizvodnih površina (desno)**

in the 3D model of particular shipyard together with the existing state in this shipyard, Figure 8. Furthermore, based on such model, the authors suggest the use of simulation modelling for analysing the throughput of the selected optimal design layout for defined production program.

Based on the same model, the material flow chart has been defined. Such material flow determined by the proposed methodology is mostly straight forward and without backward characteristics.

## 5 Conclusion

Within this research the lack of using modern scientific methods, techniques and tools for production area layout design was identified. Therefore, the goal of this research was defined, i.e. a new methodology for shipyard production area layout design was developed. Furthermore, additional effort was made to make this methodology more efficient and applicable especially for shipyard management.

Developed methodology is realised through defined procedure of four phases with the use of specially selected scientific methods and tools.

This methodology was verified on a real problem within the project of technological modernisation of an existing shipyard. The application of the developed methodology resulted in such a design solution which improved shipyard production areas layout and at the same time optimally satisfied all given criteria. Such design solution was the basis for further detailed calculations.

Furthermore, for the future research the authors suggest application of this methodology for designing optimal layouts within particular production areas of a shipyard.

## References

[1] KARRAY, F., ZANELDIN, E., HEGAZY, T., SHABEEB, A.H.M. and ELBELGATI, E.: "Tools of Soft Computing as Applied to the Problem of Facilities Layout Planning", IEEE Transaction on Fuzzy Systems, Vol. 8, No. 4, p. 367-379, August 2000.

[2] SINGH, N. AND WANG, M.H.: "Concurrent Engineering in a High Variety Label Printing Environment", International Journal of Production Research 32(1994)7, p. 1675-1691,.

[3] EPSTEIN, S. L., MOULIN, B., CHAKER, W., GLASGOW, J. I., GANCET, J.: "Pragmatism and Spatial Layout Design", COSIT 2001, p.189-205, 2001.

[4] ABDINNOUR-HELM, S., HADLEY, S.W.: "Tabu Search Based Heuristics for Multi-Floor Facility Layout", International Journal of Production Research, 38(2000)2, p. 365-383.

[5] TOMPKINS, J.A., WHITE, J.A., BOZER, Y.A. and TANCHOCO, J.M.A.: "Facilities Planning", 3rd Ed., John Wiley Inc., NY, 2002.

[6] AHMAD, R. A.: "An Intelligent Expert System for Decision Analysis and Support in Multi-Attribute Layout Optimization" University of Waterloo, Ontario, Canada, 2005.

[7] BURKE, E.K., KENDALL, G., WHITWELL, G.: "A New Placement Heuristic for the Orthogonal Stock-Cutting Problem", Operations Research 52(2004)4, p. 665-671.

[8] MATULJA, T.: "Hierarchical Modelling as Basis of the Methodology for Shipyard Production Layout Design", PhD Thesis, Faculty of Engineering, Rijeka, 2009.

[9] MUTHER, R. "Systematic Layout Planning", Second edition, ISBN: 0-933684-06-1. Management & Industrial Research Publications. USA, 1973.

[10] FAFANDJEL, N., RUBEŠA, R., MATULJA, T.: "Improvement of Industrial Production Process Design Using Systematic Layout Planning", Strojarstvo (ISSN 0562-1887), 51(2009)3, p.177-186.

[11] DONAGHEY, E., C., CHUNG, A., C., KONG, H., PIRE, F., V.: "BlockPlan 1.5", Department of Industrial Engineering,

Cullen College of Engineering, University of Houston, USA, 2006.

[12] SAATY, T. L.: “Multicriteria Decision Making“, ISBN: 0-9620317-2-0, RWS Publications, USA, 1996.

[13] SAATY, T. L.: The Analytic Hierarchy Process“, ISBN: 0-07-054371-2. McGraw-Hill, Inc. USA, 1980.

[14] WINSTON, W. L.: “Operations Research: Applications and Algorithms”, Publisher: Duxbury Press; 4 edition, ISBN: 0534380581. 2003.

[15] HILLIER, F. S., LIEBERMAN, G. J.: “Introduction to Operations Research”, 7th edition, McGraw Hill, ISBN 0072321695, 2001.

[16] EXPERT CHOICE, INC.: “Expert Choice software 11”, Arlington, VA, USA, 2004.

## Nomenclature

*AHP* - Analytic Hierarchy Process
*A* - absolutely necessary closeness
$A_{1i}$ - local priority of the *i*-class alternative regarding criterion 1,
$A_{2i}$ - local priority of the *i* -class alternative regarding criterion 2,
$A_{3i}$ - local priority of the *i* -class alternative regarding criterion 3,
$A_{4i}$ - local priority of the *i* -class alternative regarding criterion 4,
$A_{5i}$ - local priority of the *i* -class alternative regarding criterion 5,
$a_{ij}$ - Saaty’s intensity of relative importance
*BIL* - locksmith and craft workshop
*E* - essential closeness
$\partial F$ - goal function
*I* - important closeness
$K_{1\text{-}5}$ - criteria
*m* - number of experts
*MOT* - engine workshop
*NAV* - berth
$n_p$ - number of production areas
*O* - ordinary closeness
*OD1* - area for section assembling and finalizing
*OD2* - area for section finalizing
*PAN* - panel line
$P_i$ - overall priority of *i*-class,
*RIC* - pipe cutting, forming and outfitting
$r_{jk}$ - closeness rating for *i-th* closeness form *k-th* expert
*ROL* - plate cutting and forming
*ROP* - profile cutting and forming
*RPM* - subassembly
*RRL* - plate cutting
*s* - SLP score
$S_x^F$ - sensitivity function
*SEA* - sea
*SKL* - steel stockyard
*SLP* - Systematic Layout Planning
*U* - unimportant closeness
$w_i$ - weight factor for *i-th* closeness
*X* - not desirable closeness
*Yi* - number of closeness of *i*-class
*ZBO* - equipment blasting and painting
*ZIB* - section blasting and painting