AUTOMATED DECK LAYOUT DESIGN

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SUMMARY

This article presents the further development of the automated deck layout design. Efficient spatial arrangement is crucial for ships having large number of people on board e.g. ro-pax. Procedure starts with the list of required rectangular compartments while it ends with their optimal locations within available deck space. A two-phase multi-criteria procedure is developed consisting of the automated layout generation phase and of the decision making phase. Compartments are limited by their minimal dimensions lengthwise and crosswise and by required minimal area. Heuristic algorithm for placing, creating and modifying compartments within available deck space is developed. By allowing dimensional variability of each rectangular compartment, considerable improvement in flexibility of the Pareto-optimal solutions is reached. Pareto-optimal layout designs make possible the trade-off between different optimal solutions in the multi-attribute environment. The procedure is applied to the deck layout design of the ro-pax vessel. The graphical output helps to visualize different solutions.

1. INTRODUCTION

Automated layout generation by standard optimization methods (e.g. knapsack problem or other packaging problems) is hardly applicable to the deck layout design since adjacency and relative placement of different ship compartments have to be taken into account [1][2]. Heuristic algorithm for placing compartments within available deck space, based on the Monte Carlo method, presented in [3] is further developed. The coordinates of the compartments are variables of the problem. Cumulative value of pair wise relations of all compartments within one layout is used as an attribute for decision making procedure. The higher the value of an attribute the better is the layout in respect to that attribute. Following good practice in layout design, a modular grid is used to locate compartments and every individual rectangular compartment is defined using the same module as an unit.

Assuming a list of variable size of rectangular compartments is given, the layout is defined by a set of coordinates of all compartments. A two-dimensional case with all compartments defined by their footprints is treated here.

The new procedure for placement of compartments is developed by following original method of placement in one-compartment layers but mirroring complete deck about centerline axes before proceeding with the placement of the next layer.

Placement of the compartments is subject to geometric constraints of not intersecting between themselves or with deck boundary. Other criteria include the efficiency of deck area utilization, adjacency of selected compartments, distance of compartments, connectivity of the compartments, communication between compartments, natural lighting, etc. Due to vertical communication (e.g. stairs, lifts, ducts, etc.) selected compartments are fixed so the procedure takes care of that constraint.

It is assumed that it is possible to express designer's intentions by membership grade functions applied to each attribute.

Layout arrangement is defined by the list of compartments and by their relations, in three phases:

- Variation of compartment dimensions.
- Placement of compartments – generating topological solutions.
- Calculation and valuation of each placement solution.
- Pareto candidate selection.

Relation of the two compartments is viewed as their distance and their adjacency. Distance determines closeness or remoteness of two compartments, or the compartments and the sides of given zone or a fixed compartments. Adjacency relates to the level of communication between two compartments.

Every compartment is named after the assigned function, and numbered if several identical compartments are needed. Most used types are: hold, void, cabin, corridor, hall, restaurant, galley, sanitary, stairway, lift, vent, casing, etc.

Design procedure is limited to one zone clearly separated from other zones of the ship. Typical is one fire zone, but other criteria are acceptable as well, e.g. restriction due to flooding containment. A zone can be defined by the fixed dimensions or a variable dimensions using modular design grid.

2. TOPOLOGICAL SOLUTIONS

The result of topological solution is the placement of all compartments within given zone envelope. Selection of the type of compartments, the size of compartments and their function is defined at the higher level of design procedure.

Starting with the given types of compartments (e.g. casing, stairway, cabin, corridor, saloon, restaurant, galley, etc.) designer ends with their optimal locations within available deck space. Different criteria and constraints are applied in the process. Placement of the compartments is subject to geometric constraints of not intersecting between themselves or with given zone. Orientation and placement of a compartment relative to the boundary (i.e. superstructure or deckhouse sides) is valued in respect to the desirable or required placement. Due to vertical communication (e.g. stairs, lifts, ducts, etc.) selected deck locations may be occupied in advance and the procedure takes care of that constraint too.

2.1. PLACEMENT OF THE COMPARTMENTS

All possible combinations of placing given set of compartments within given zone leads to numerical explosion even for moderate number of compartments. Placing 28 compartments within a given zone, of the example ro-ro vessel, leads to the 3.05 x 10^{29} possible solutions.

Layout problem belongs to the group of NP-complete problems (i.e. Non deterministic Polynomial-complete) for which a time needed for solution cannot be bounded by the polynomial having size of the problem for a variable. Typical problem of the sort is the well known "traveling salesman problem" that is easily solved for small number of elements but it is not possible to find exact optimum for large number of elements.

A number of possible solutions may be found and their relative value may be determined via multi attribute procedure. Here a Pareto-optimal boundary is established for a 6-attribute problem.

Considerable improvement of the method of compartment placement was obtained by mirroring the zone after completing one layer. Due to selected method of placement as described in 3.1 and Figure 5, lot of searching was needed in order to complete the last layer. After mirroring of the zone about the centerline axes the process of placement virtually starts from the beginning.

Finally, mirroring will take care of returning the zone in original position. This procedure saves considerable amount of time as compared to the same procedure without mirroring. At the same time better space utilization is reached with less iterations. The procedure of the compartment placement with mirroring is demonstrating in sequence of figures from Figure 1 to Figure 4.

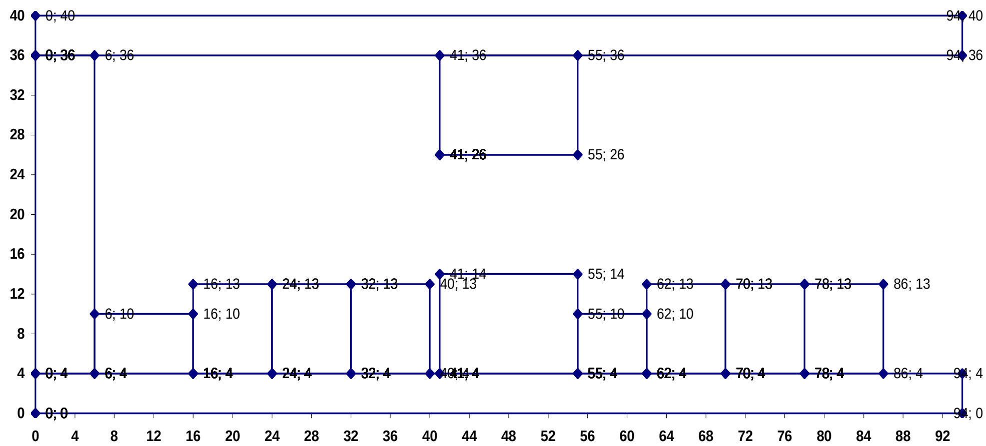

Figure 1. Placement of compartments of starboard of the zone

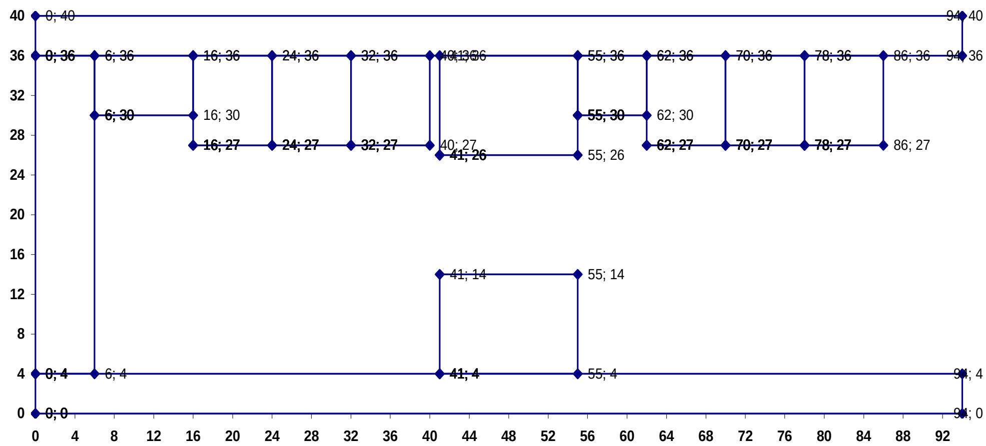

Figure 2.Phase of first mirroring of the placed compartments

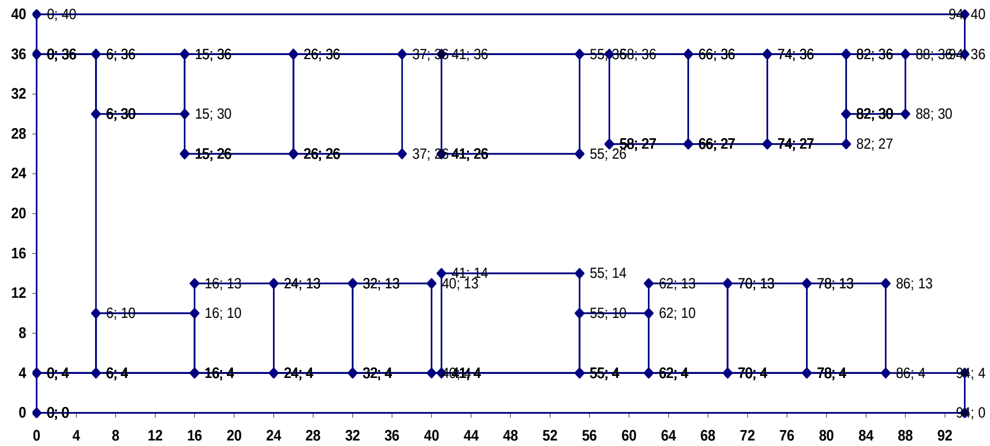

Figure 3. Placement of the compartments on the port side of the zone

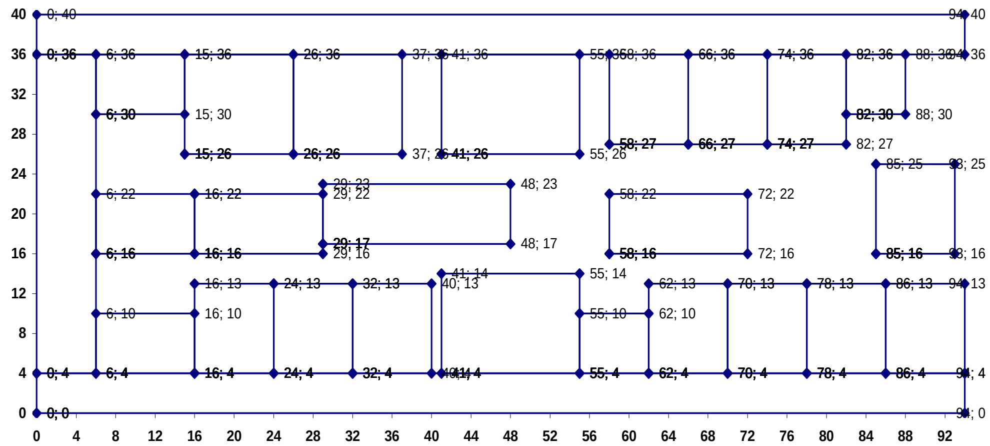

Figure 4. Phase of second mirroring and placement the rest of the compartments

2.2. OPTIMIZATION METHODS

Standard optimization approach for this sort of problems refers to the "knapsack" problem where the task is to place as many as possible individual boxes (here compartments) within given zone. This approach is useful for solving problems where relations of the elements are not important, e.g. container loading problem.

In principle there are two basic approaches: *3-D bin-loading problem* [1], where it is required that all given elements are placed within minimal number of containers and, the alternative one *3D knapsack-problem* [2], where maximal weight must be loaded within given container while some of the elements may not be loaded.

Majority of the "knapsack" algorithms begin with sorting compartments by size starting with the largest one and placing starts from the lower left corner. While good space utilisation may be reached, "knapsack" procedure cannot address the problem of the adjacency and/or distance of compartments.

3. THE MARRSD METHOD

The MARRSD (**M**odular **A**pproach to **R**o-**R**o **S**hip **D**esign) method was developed in order to solve problems of compartment interaction and communication in addition to the space utilization of ro-ro ships [3], although it is applicable to other layout problems as well. The method is based on the heuristic algorithm that utilizes random selection of order of compartments and searches for the next free position in the layout grid. Since in the multi-attribute environment there is no unique optimum, the design space is searched in order to find non-dominated solutions. Pareto optimal (or non-dominated) solution is the one that is better than any other solution in at least one attribute. Infeasible solutions are eliminated automatically by the method of placement of next compartment. The ideal feasible design, named "Utopia", that is defined by the set of most desirable attributes found in all solutions, is clearly infeasible since it is composed of the attribute values that do not belong to the single design. Set of non-dominated solutions is subsequently used to select one preferred design. Here a design having minimal distance to Utopia is accepted as a preferred design although other solutions are possible.

Attributes of pair wise relations between compartments are:

- Distances between ordinary compartments.
- Distances to the zone boundaries (fore, aft, port and starboard).
- Distances between ordinary and fixed compartments.
- Communication i.e. adjacency between compartments.
- Corridor access criteria.
- Zone utilization by the compartments.

3.1. IMPROVEMENTS OF THE MARRSD METHOD

In order to facilitate better utilization of the available deck area a more realistic treatment of compartment size is introduced. Size of the compartments is not fixed as it was in previous version. Compartments are limited by their minimal dimensions lengthwise and crosswise and by the required minimal area. All compartments of the same type (e.g. cabins) are identical during one design cycle. Before starting next optimization cycle dimensions of variable compartments are changed by the separate procedure.

Each compartment is flexible within three constrains. The first constraint is minimal required area which is applicable to the proposed habitability standard. The second and the third constrains reefer to minimal required dimension lengthwise and crosswise respectively. Constraining minimal dimensions takes care of the required space for placement of critical items (e.g. cabin length > berth length + passage width). Product of the compartment minimal beam and minimal length must be less or equal to the minimal required area. Any number of compartment types may be made variable or may be fixed in size.

If the product of these dimensions is exactly equal to minimal area, it means that the compartment size is not variable. If, at least one dimension is greater than minimum, the actual compartment area may be equal or larger than minimal area. Variation is performed within minimal and maximal dimensions where maximal dimension in one direction is obtained by dividing the minimal area by the minimal dimension in the other direction. This approach enables creation of compartment larger than minimally required. If a compartment is larger than minimally required it is assumed that its function is better fulfilled than one of smaller compartment and will rewarded in the process of decision making.

Since all compartments of the same type are identical there is no preference for better placement among themselves. All compartment of the same type occupy the same row and column in the desirability matrix, therefore reducing its size and making it more user friendly.

Option of fixing size and location of the selected compartments is retained as described in [3].

On the Figure 5 search algorithm for the searching of the not occupied knot is presented. The search for available free knot proceeds from left to right at the lowest free location and, after reaching the side of given zone, process proceeds by one grid module up.

Initially the compartment is placed in the first free location and in sequence all knots that the compartment would occupy are tested. If all knots are free, the compartment is placed and all the knots belonging to it are marked as occupied.

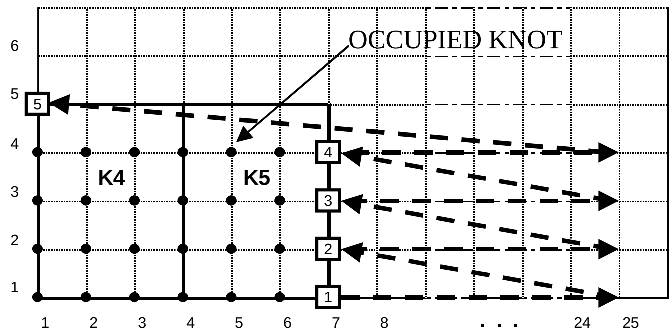

Figure 5. Searching for the free knot

3.2. TREATMENT OF CORRIDORS

The important innovation in the automated layout design is the treatment of corridors. While corridors were originally treated as fixed size predefined compartments, now they are treated as flexible connection between compartments and open deck. Interesting variant of definition of corridors is given in [4].

Tracing corridor path is performed by a specialized procedure, structured in two steps. Previous treatment of the corridors as a compartment of a given size created lot of difficulties when contiguous corridor was required. The new method of creating corridor as a remaining free space between all other compartments is much faster and produces a natural communication path to all compartments (e.g. Figure 18).

The first of the two steps assigns corridor element of the given width I_CORR to the specified side of each compartment whether fixed type or ordinary type. This is marked on the following pictures (Figure 6. to Figure 11.) with angled hatch. The second step makes connections between this individual corridor elements thus creating a contiguous corridor. This is marked with cross angled hatch. We have introduced the following variables to control this process:

K1= XPF(J) - (XK(I)+1)
K2= XKF(J) - XK(I)
K3= XP(I) - (XKF(J)+1), where

XP and XK are the coordinates of ordinary compartments in allocated zone i.e. start-points and end-points respectively. While XPF and XKF are the coordinates of the fixed compartments in allocated zone i.e. start-points and end-points respectively. For the case definition we have used widths HH(I) and HHF(J) of ordinary and fixed compartments respectively. Also, we have introduced variable IDI as the predefined controlled distance between two compartments. It is advisable to set this value not less than width of corridor I_CORR.

Four cases of relative placement of ordinary and fixed type of compartments are determined as follows (Figure 6. to Figure 9.):

1. Case: Variables K2 > 0 and (K1 $\geq$ 0 and K1 $\leq$ IDI), HHF(J) > HH(I)
2. Case: Variables K2 > 0 and (K1 $\geq$ 0 and K1 $\leq$ IDI), HHF(J) < HH(I)
3. Case: Variables K2 > 0 and (K3 $\geq$ 0 and K3 $\leq$ IDI), HHF(J) > HH(I)
4. Case: Variables K2 > 0 and (K3 $\geq$ 0 and K3 $\leq$ IDI), HHF(J) < HH(I)

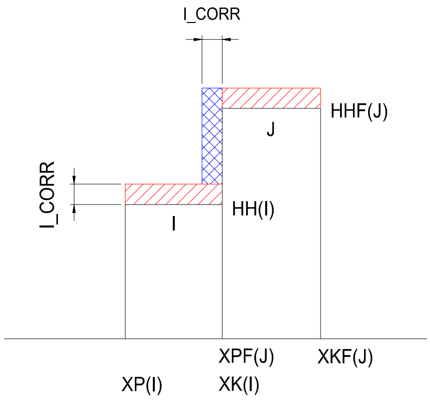

Figure 6. 1st case - fixed compartment J is at the right side of the I compartment and its width is larger

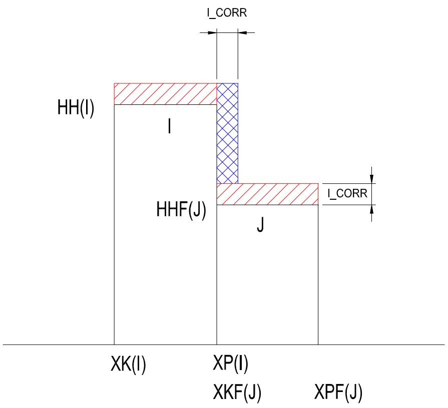

Figure 7. 2nd case - fixed compartment J is at the right side of the I compartment and its width is smaller

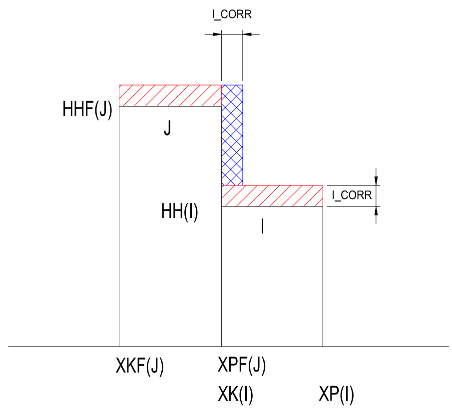

Figure 8. 3rd case - fixed compartment J is at the left side of the I compartment and its width is larger

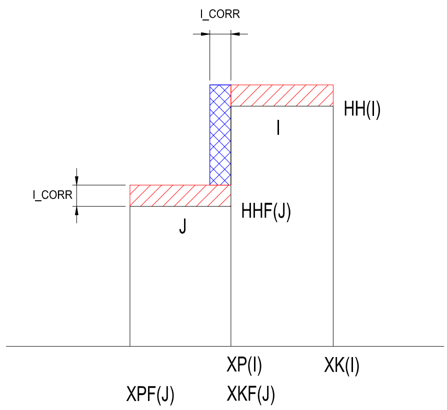

Figure 9. 4th case - fixed compartment J is at the left side of the I compartment and its width is smaller

Similarly, the relationship between the two adjacent compartments is defined by two cases instead of four as previously explained. Here, variable K4 is defined to control the process as:

K4=XP(I)-(XK(I-1)+1), where

the XP and XK values are already explained.

The two cases of relative placement of two ordinary compartments are determined as follows (Figure 10. and Figure 11.):

1. Case: Variables K4 $\geq$ 0 and K4 $\leq$ IDI), HH(I) > HH(I-1)
2. Case: Variables K4 $\geq$ 0 and K4 $\leq$ IDI), HH(I) < HH(I-1)

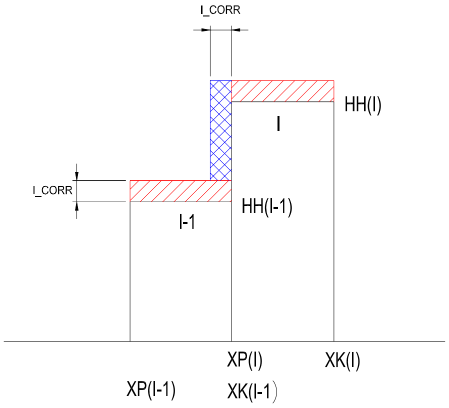

Figure 10. 1st case of relative position of two compartments: I compartment width is larger than the I-compartment width

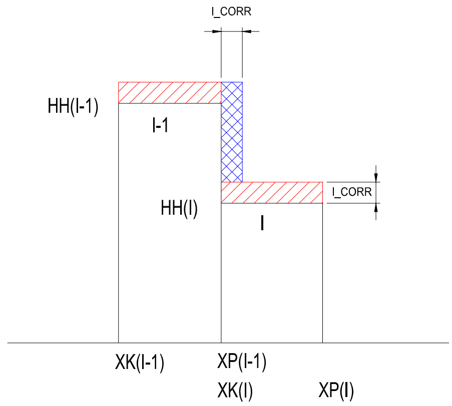

Figure 11. 2nd case of relative position of two compartments: I compartment width is smaller than the I-compartment width

4. CALCULATION AND VALUATION OF LAYOUT SOLUTIONS.

After placing all compartments, the procedure calculates the distances between compartments and distances to the sides of the given zone, so as distances to the fixed compartments. The 6 cases of possible relative location of any 2 compartments are identified [3].

Six attributes are relevant for every feasible layout:

- Y1 - distances between any 2 ordinary compartments.
- Y2 - distances to the zone boundaries.
- Y3 - distances between ordinary and fixed compartments.
- Y4 - communication i.e. adjacency between compartments.
- Y5 - corridor access criteria.
- Y6 - zone utilization by the compartments.

Communication between two compartments is determined by the maximum allowed distance and by the minimal required size of overlapping. Overlapping is defined as an intersection of orthogonal projections of compartments. If two compartments are at distance AH=0 and AW is grater than zero, the compartments are in contact and the size of overlapping is AW.

The distance U between the pair of compartments is calculated as:

$$U = \sqrt{AW^2 + AH^2} \qquad (1)$$

Values of Y5 and Y6 indicate the level of utilization within given zone. The respective intensity matrices, given by the designer, define preferred values of the attributes Y1, Y2, Y3, and Y4. The designer may require remoteness or closeness of the compartments by assigning a value in the range from –9 to +9 in order to express desirability of the relative position of the pair of compartments or the compartment and the selected deck boundary. The distance between compartments is normalized by the value functions adapted from the fuzzy set theory.

Closeness is preferred by the negative intensity values (Figure 12.): Q= -9, Q= -7. Q= -5 or Q= -3, while remoteness is preferred by the positive intensity values (Figure 13.): Q= 9, Q= 7. Q= 5 or Q= 3,

Attributes of communication the intensity is expressed by Q= 9X, Q= 7X. Q= 5X or Q= 3X, (Figure 14.). The value of X in the expression refers to the orientation of the communication: X=1 stands for indifference, X=2 indicates transverse direction, X=3 expresses longitudinal direction. Figure 12., Figure 13. and Figure 14. have the abscissas expressed in the number of grid modules and ordinates represent the membership grade *m* with values between 0 and 1. Membership grade signifies a level of desirability of reaching certain level of the respective attribute, e.g. close or distant, communicating or not. In this sense Q is used as weighting factor.

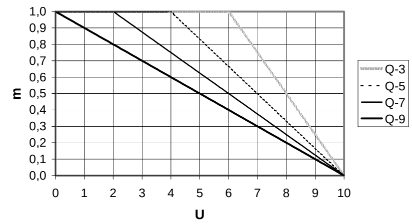

Figure 12. Membership grade for variable closeness desirability (Q-3 to Q-9)

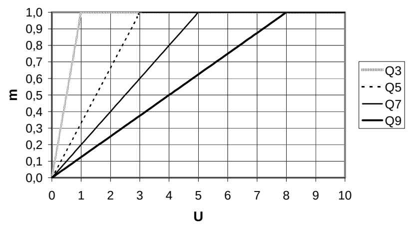

Figure 13.Membership grade for variable remoteness desirability (Q3 to Q9)

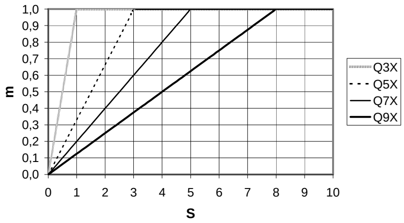

Figure 14.Membership grade for variable overlapping desirability (Q3X to Q9X)

The complete procedure is programmed in Visual FORTRAN and number of iterations is monitored.

5. CASE STUDIES

Example of the application of the procedure to a ro-pax vessel layout (Figure 15 to Figure 21) is demonstrated in sequel. Graphical presentation of different solutions is done by a Visual Basic programmed macro in MS Excel.

Theoretical number of combinations is the number of permutations of *n* elements (compartments) is given as:

$$P_n = 1 \cdot 2 \cdot 3 \ldots \cdot n = n! \qquad (2)$$

Since improved method performs search in two loops, the first dealing with compartment variation and the second dealing with compartment placement, different choices are possible.

It may be noticed that less than placements is not giving satisfactory layout. Figure 15., Figure 16., Figure 19. and Figure 20., while Figure 17. shows better layout result.

Figure 18. and Figure 21. demonstrate optimal layouts reached in one million iterations. It may be concluded that for the 33 (28 ordinary and 5 fixed) compartment problem about one million iterations are producing optimal layout

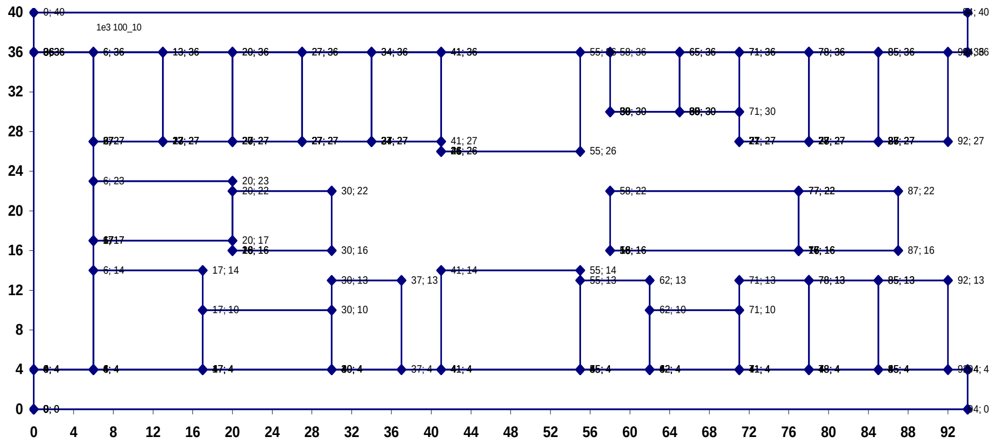

Figure 15. 1000 iterations – 100 dimension variations and 10 placements

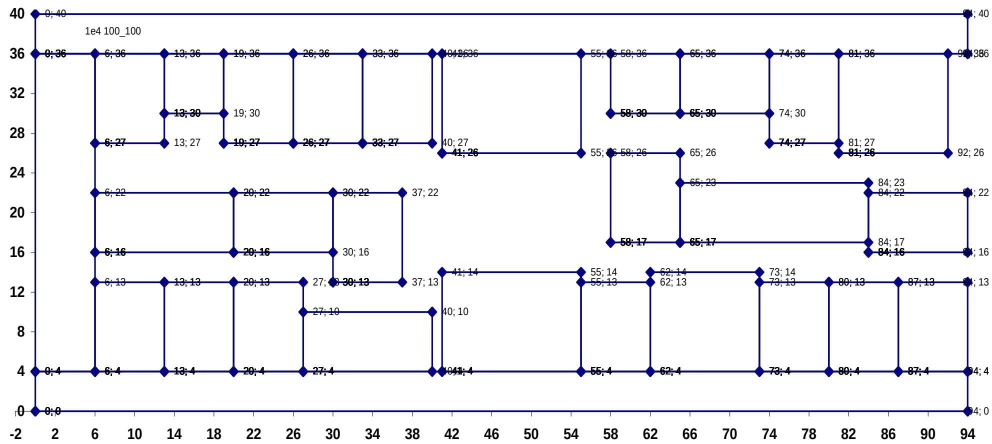

Figure 16. 10000 iterations – 100 dimension variations and 100 placements

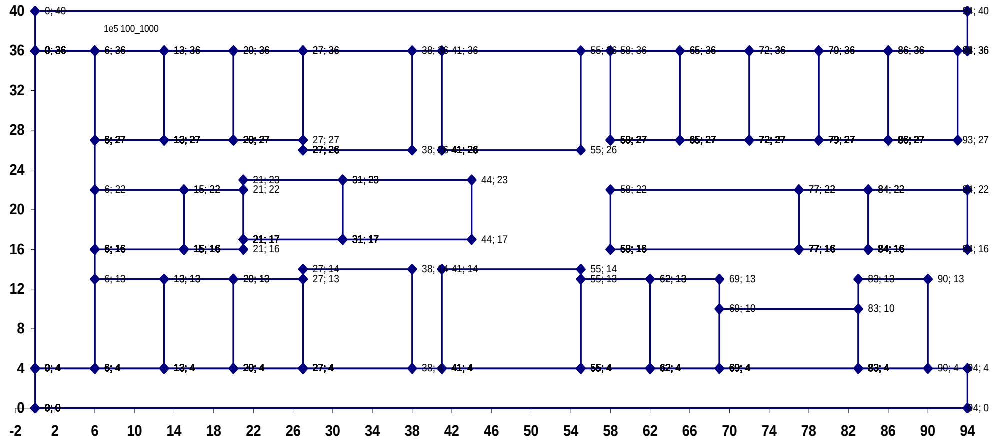

Figure 17. 100000 iterations – 100 dimension variations and 1000 placements

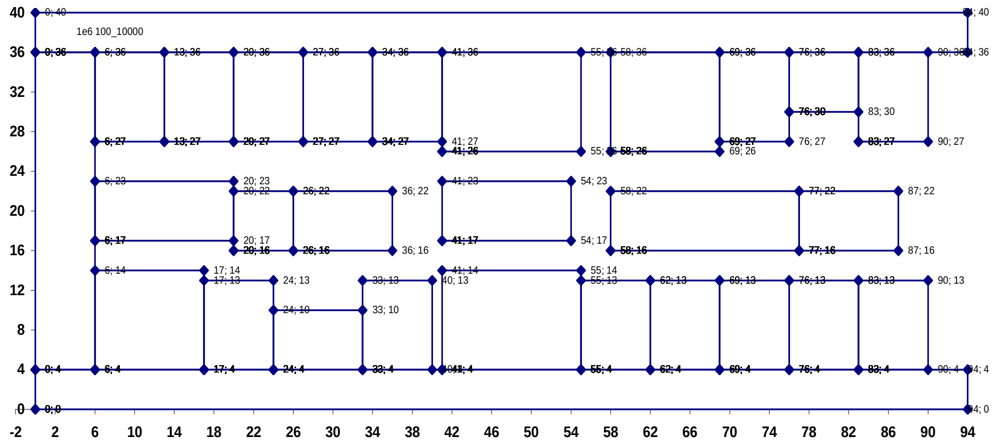

Figure 18. One million iterations – 100 dimension variations and 10000 placements

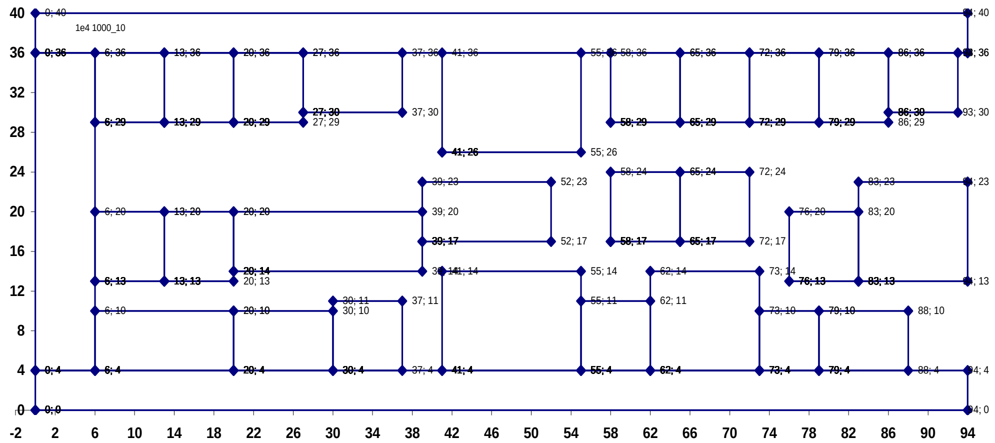

Figure 19. 10000 iterations – 1000 dimension variations and 10 placements

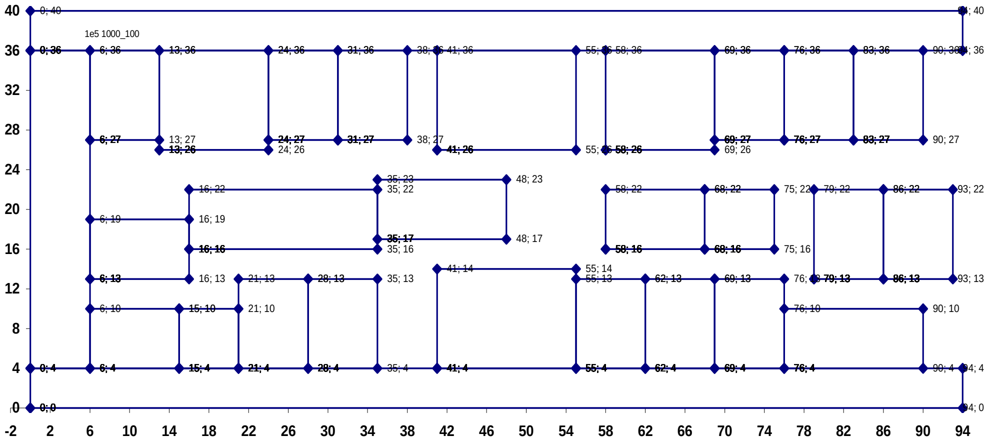

Figure 20. 100000 iterations – 1000 dimension variations and 100 placements

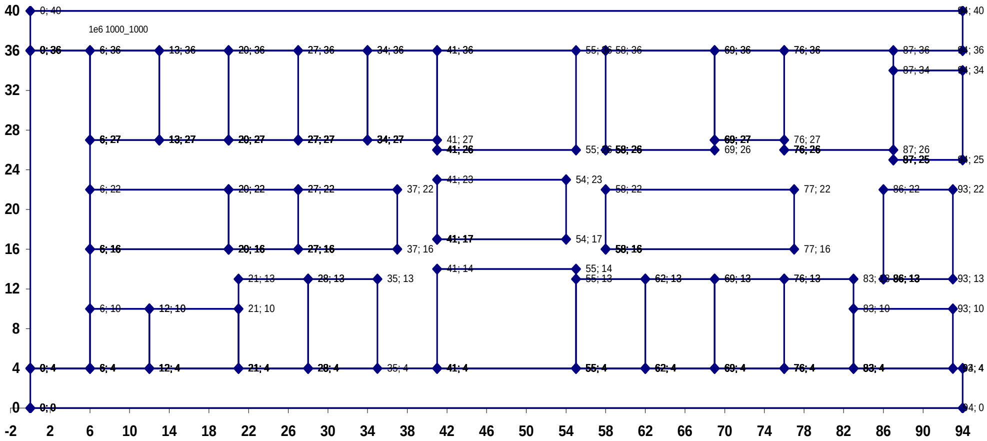

Figure 21. One million iterations – 1000 dimension variations and 1000 placements

6. PARETO-OPTIMAL CANDIDATE SELECTION

Since more than one attribute is used, there is no single optimum and the decision-making is based on the principle of non-dominance. Consequently the Pareto-optimal layout designs are filtered by the elimination procedure that makes possible the trade-off between different optimal solutions in the multi-attribute environment. The design is Pareto-optimal if it is not possible to improve on any attribute value without worsening at least one of the remaining attributes [5].

Utopia $UP1$ is defined by the set of attribute maxima of all Pareto-optimal designs:

$$UP1 = (MY1, MY2, MY3, MY4, MY5, MY6) \qquad (3)$$

, where *MY1...MY6* stand for attained maximal values of attributes *Y1..Y6*.

Distance $DP1$ from any design to Utopia is calculated by the Euclidean metric:

$$DP1 = \sqrt{(MY1 - PY1)^2 ...(MY6 - PY6)^2} \qquad (4)$$

Ideal point $UP2$ is defined by the set of attribute theoretically maxima.

$$UP2 = (1,1,1,1,1,1) \qquad (5)$$

The theoretically maximal normalized distance $DP2$ is calculate as follows:

$$DP2 = \sqrt{(1 - PY1)^2 ...(1 - PY6)^2} \qquad (6)$$

, where *PY1...PY6* stand for attribute values of attributes *Y1...Y6*, belonging to the selected design. Distances of all designs are sorted in ascending order where the closest design to Utopia is the preferred one. Designs are grouped and marked by different symbols in relation to the distance.

In Figure 22 an example of the hyper-plane of Pareto-optimal 592 designs for 32-compartment problem is presented graphically. Attribute Y1 is related to attribute Y6.

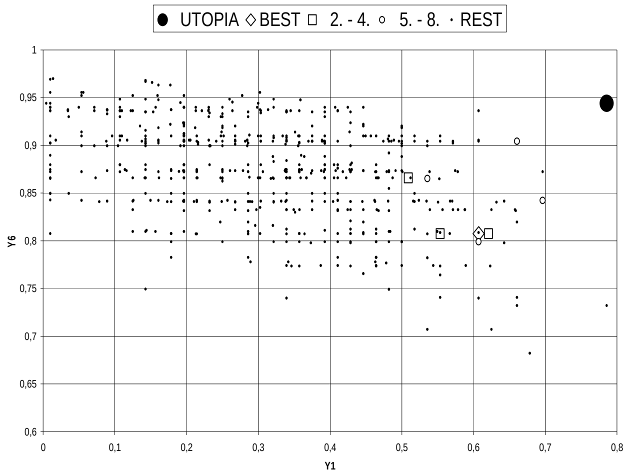

Figure 22. Relation of attributes Y1 and Y6 for the case 1000 x 1000 iterations

7. CONCLUSION

- The proposed procedure demonstrates that it is feasible to apply heuristic algorithm to the problem of layout optimisation of the ship accommodation zone.
- Improvements of the procedure as demonstrated in this article achieved optimal layouts in shorter time than before and provides much better access to each compartment by creating corridors using specialized procedure.
- The 32-compartment layout problem is close to practical designer's problem and will be further tested in design work. Figure 23. shows how number of variation of compartment dimensions and number of placements is related to distance *DP*2 i.e. how the layout is getting better by different number of iterations.
- Some further experimenting is needed in order to improve the application of intensity grades and other membership functions.

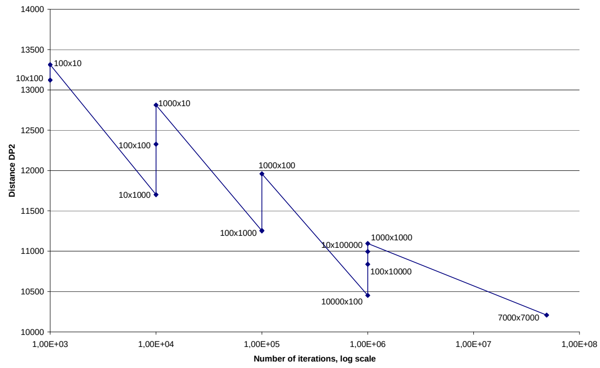

Figure 23. Distance DP2 in relation of number of iterations

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