Developing feasible stowage plans by means of an evolutionary algorithm

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ABSTRACT

This paper presents a proof of concept for a ship stowage plan generator. The Royal Netherlands Navy foresees a significant need for expeditionary operations in the future involving ship-shore connections of equipment and personnel. Given the associated demand of amphibious lift capacity and logistic support, an efficient and safe distribution of the equipment onboard the ships is an important factor for a successful operation. A stowage plan is a combinatorial optimisation problem that can be solved by a genetic algorithm. A proof of concept is implemented in a loading computer software application and a case study has been included in this paper, as well as recommendations for further development and future investigation.

KEY WORDS

Stowage plan, Genetic algorithm, Landing Platform Dock, Optimisation

1. INTRODUCTION

Several navies are dealing with a growing demand of operations for amphibious warfare ships, also called Landing Platform Dock's or LPD's. These warships embark, transport, and disembark equipment of a landing force for expeditionary missions. They are designed to transport troops into an area by sea, primarily using landing craft possibly supported by helicopters. The LPD's are designed to transport a wide range of equipment (landing craft utilities, helicopters, RoRo cargo, containers) and other cargo (fuel, food, munitions and hazardous substances).

Given the associated demand of amphibious lift capacity and logistic support, an efficient and safe distribution of the equipment onboard ships is one of the major conditions for a successful operation. The stowage plan shows the position of each piece of cargo unit onboard and the resulting overall loading condition has to comply with safety criteria, ship criteria and user criteria.

Designing the stowage plan used to be performed by hand, since stowage plans are based on many complex human-based decisions. However this method is highly time-consuming and not necessarily optimal. Moreover, the individuals (both onboard and ashore) involved in setting up a stowage plan and assessing the ship safety are not necessarily the same. As a result, the ship safety which needs to be assessed with the (onboard) loading computer software is not directly taken into account by the stowage planner. Designing a conceptual stowage plan by hand, checking the safety with the loading computer and finalising the stowage plan, now generally requires several days of work.

A research program was commenced in order to investigate the possibilities to implement an automatic stowage plan generator for mixed RoRo cargo into the loading computer software of an LPD. Several studies have been done to investigate potential layout problems, packing problems and space allocation. This paper presents a novel study to use an evolutionary algorithm designing stowage plans by computer that secures safety and takes ship criteria and user criteria into careful account.

2. LANDING PLATFORM DOCK

This proof of concept demonstrates a methodology to develop feasible stowage plans by a generator that is implemented in a loading computer software application. The generator should be easily configurable for implementation on different LPD's or other ship types. The example LPD has two helicopter landing spots and a well dock in which two Landing

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Craft Utilities (LCU's) can be berthed. To transport a wide range of equipment the LPD has two decks. On the first level the well dock, main vehicle deck and low vehicle deck can be found. The second level consists of a flight deck and hangar. Figure 1 shows the side view of the LPD.

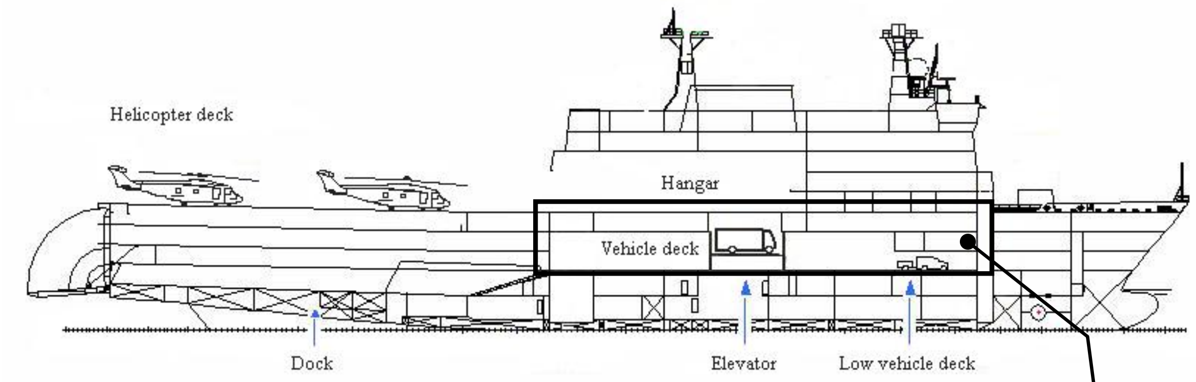


Figure 1: Side view of the example LPD.

RoRo cargo can reach the flight deck by means of an elevator between the main vehicle deck and hangar. A crane located on top of the flight deck is able to lift RoRo cargo from the quay side onto the flight deck. The maximum lift capacity for both the elevator and crane is 25 ton.

The layout of the decks on the first level is shown in figure 2. Lashing points can be found all over the deck, which can be divided into small lanes and wide lanes. After embarking each piece of equipment is lashed to the deck by securing it to four different lashing points.

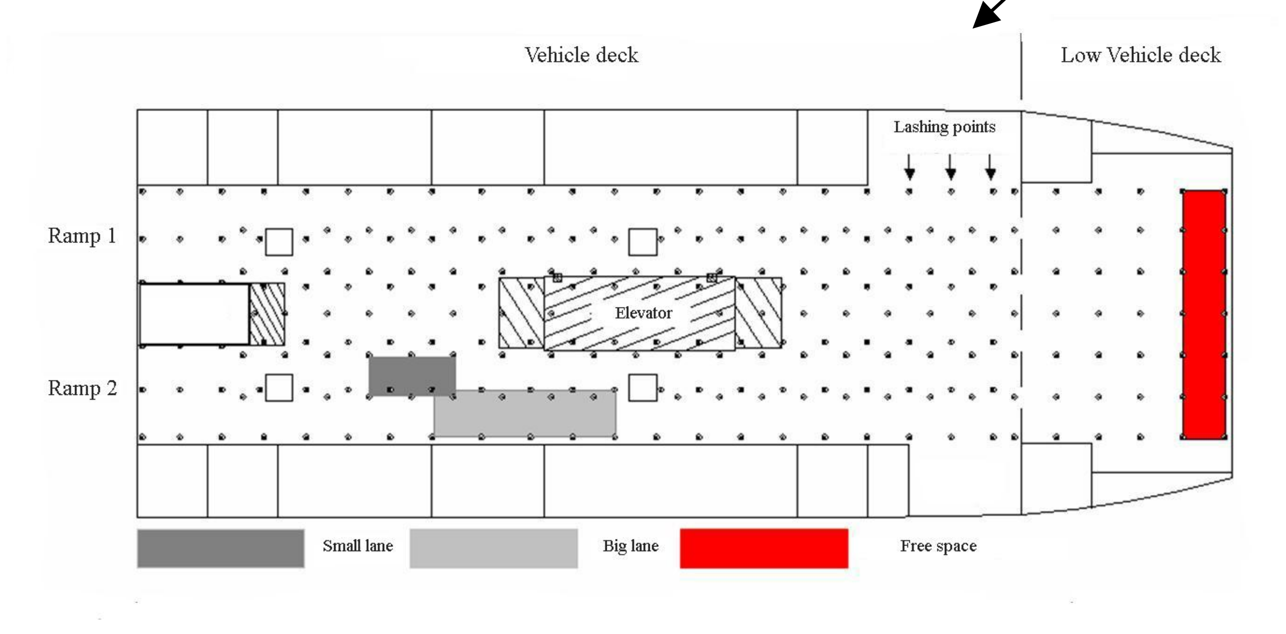


Figure 2: Top view of main vehicle deck.

The LCU's are positioned aft of ramp 1 and 2, hence the RoRo cargo can be rolled on both LCU's at the same time. The LCU can transport an approximate amount of 10 vehicles per crossing (depending on size and weight).

To support amphibious landings, the Beach Armoured Recovery Vehicle (BARV) and mats are standard equipment for a LPD. The BARV is used to re-float landing craft and to recover vehicles that got stuck at the beach ashore. A so-called CASE can transport and unroll special mats at the beach to prevent vehicles of getting stuck.

3. RELATED RESEARCH

Research has been done to find a possible solution for the Stowage Plan Generator (SPG). Several studies on layout problems, packing problems and space allocation have been studied to find possible solutions. Allocating small objects into big objects concerning certain constraints is the essence of all related 'layout' problems.

An interesting application area is the facility layout problem, which concerns the allocation of activities in such a way that a set of criteria (e.g. area requirements) are met and/or some objectives are optimised (usually measured in some type of costs). Facility layout problems vary in scale from the assignment of activities to cities, sites, campuses or buildings and to the location of equipment and personnel groups on a single floor of a building. The proposed algorithm that is currently widely used for facility layout problems is the Genetic Algorithm (GA), (Ligget 2000, Drira 2000, Lee 2005).

A proof of concept for an optimisation-based allocation approach for the conceptual design of ships is shown in e.g. (Van Oers, 2007). To develop feasible ship designs a search algorithm is needed, that can search for large numbers of feasible concept designs. Optimisation algorithms allow users to efficiently search in the exploration space for the 'best' designs, in e.g. (Van Oers, 2007) a multi-objective search method is applied.

4. PROPOSED ALGORITHM

The SPG is a combinatorial optimisation problem, since a number of sub-functions need to be optimised by taking several constraints into account. The main goal for combinatorial optimisation problems is to find the best out of all possible solutions by optimising several sub-functions. The term to optimise for the SPG means finding a solution which is the best for all (incompatible) sub-functions.

A computer can first generate each possible stowage plan and an algorithm can evaluate them subsequently to find the best. When stowing just a small amount of equipment, there will be billions of different solutions that need to be generated and evaluated.

Table 1 shows the number of possible solutions for one to twelve vehicles. In this example cargo can only be positioned at N places, equal to the number of vehicles. The number of possible solutions increases exponentially. Cargo on the LPD can be positioned from ten to hundreds of different positions, depending on the type of cargo. Evidently, the amount of RoRo cargo transported by the LPD is much higher than twelve. It is therefore computational impossible to generate and evaluate all possible solutions. The SPG can be classified as NP-hard (nondeterministic polynomial-time hard).

Table 1.

N	Possible solutions	N	Possible solutions
1	1	7	5 040
2	2	8	40 320
3	6	9	362 880
4	24	10	3 628 800
5	120	11	39 916 800
6	720	12	479 001 600

Metaheuristics are capable to find possible solutions within an acceptable timeframe. Metaheuristics are typically high-level strategies that guide an underlying, more problem specific heuristic to increase its performance. The main goal of a metaheuristic is to avoid the disadvantages of iterative improvement and, in particular, a multiple descent by allowing the local search to escape from local optima. This escape is achieved by either allowing worsening moves or by generating new starting solutions for the local search in a more 'intelligent' way than just providing random initial solutions. The main difference between pure random search and the metaheuristic approach is the fact that metaheuristic randomness is not used blindly, but in an intelligent form.

The GA is a metaheuristic that has been studied widely (Goldberg 1989, Koza 1992, Liu 1999). Related research has proven that layout problems such as the SPG can be solved with the use of a GA. It is possible that faster and more accurate algorithms exist, but those are excluded from this proof of concept.

5. CRITERIA

Stowage plans are based on many complex human-based decisions. The stowage planner needs to comply with safety criteria, ship criteria and user criteria. He decides which (soft) criteria should be met and which not, since several criteria might be contradicting. When developing stowage plans, the decisions of the stowage planner depend on the experience, routine and the type of operation. The implementation of the line of thought of the stowage planner into a computerised SPG is one of the most complex challenges. Therefore a user must be able to easily add or delete criteria that need to be applied in the SPG.

The criteria can be divided into three categories:
1. Safety criteria,
2. Ship criteria,
3. User criteria.

5.1 Safety criteria
The safety criteria reflect intact stability, damage stability, reserve buoyancy and longitudinal strength. These requirements are normally verified based on the output from the onboard loading computer software.

5.2 Ship criteria
Besides the safety requirements the ship-specific criteria must be taken into careful account as well. To prevent the RoRo cargo from sliding, all RoRo cargo must be positioned between four lashing points and lashed to the deck. The capacity of elevators and cranes and available heights of decks are other examples of ship criteria that need to be fulfilled when a stowage plan is developed.

5.3 User criteria
Human based decisions are made by the stowage planner which are dependent on the type of mission and required equipment. Free space is allocated for elevators and shifting of cargo. The priority of disembarking every RoRo cargo is closely related to the operational mission of the ship.

Safety requirements and other ship-specific criteria which secure safety onboard for the crew, cargo and ship itself are fixed and called fixed criteria. For this proof of concept the fixed criteria in table 2 are used.

Table 2.

Fixed criteria	Description
1	Metacentric height G'M
2	Angle of heel
3	Trim
4	Maximum deck capacity
5	Heights of decks
6	Positioning cargo between lashing points

Soft criteria reflect free space allocated for elevators and shifting of cargo. For this proof of concept the soft criteria in table 3 are used.

Table 3.

Soft criteria	Description
1	Priority of disembarking
2	Shift space
3	Free spaces for elevators
4	Helicopters in hangar
5	All cargo must be loaded
6	Allocate free space
7	Standard equipment

On expeditionary missions standard equipment disembark at first to prepare the beach ashore for landing troops with their equipment. Standard equipment must be positioned in a specific area on deck to prevent them from blocking other RoRo cargo when shifting.

6. APPLICATION

The GA generates individuals that present possible solutions. A Design Algorithm (DA) decodes the individuals into actual stowage plans. Stowage plans can then be evaluated by an Evaluation Algorithm (EA) to calculate the fitness value and are thereafter send back to the GA to generate stowage plans with a higher fitness value. Figure 3 shows the schematic view of the application.

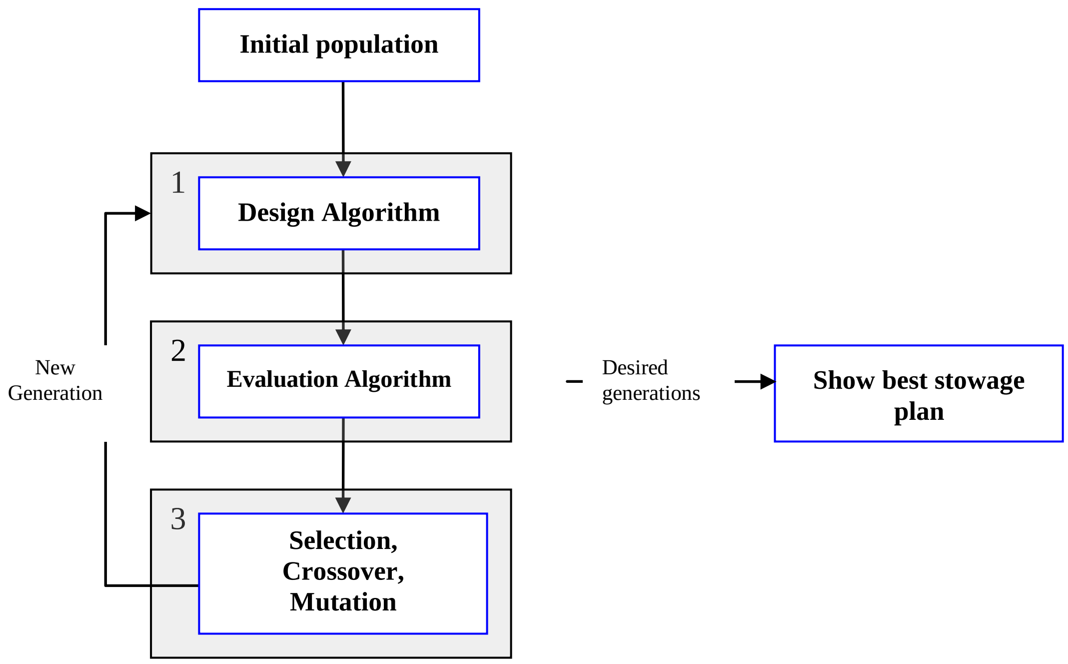


Figure 3: Schematic view of application.

A cargo list is the direct input for the program to start generating stowage plans. Table 4 shows an example of a cargo list.

Table 4.

Cargo no.	Weight (tons)	Length (meters)	Width (meters)	Height (meters)	LCG (meters)	VCG (meters)	Priority
1	*2.63*	*4.56*	*1.79*	*2.28*	*2.28*	*1.14*	*1*
2	*2.63*	*4.56*	*1.79*	*2.28*	*2.28*	*1.14*	*1*
3	*2.63*	*4.56*	*1.79*	*2.28*	*2.28*	*1.14*	*1*
4	*2.63*	*4.56*	*1.79*	*2.28*	*2.28*	*1.14*	*1*
5	*12.80*	*6.79*	*2.70*	*3.58*	*3.40*	*1.79*	*1*
6	*40.00*	*7.90*	*3.35*	*3.50*	*3.95*	*1.75*	*8*

The GA generates individuals (for example: 5 3 6 1 2 4). The length of each individual is equal to the amount of cargo pieces and each gene (cargo number) represents a RoRo cargo.

The population size is significant to the proper functioning of the application. If populations are small, the GA can converge to local optima, because the search space will be too small. Big populations will affect the calculation time so the GA will converge slowly to an optimum. A standard size of a population of 20 individuals gives the best results for the GA, (Goldberg 1989):

Population (n) = 20

Individual (In) $In_i \in population \ \{i = 1,.., population size\}$

6.1 Design algorithm

The DA decodes the individuals into stowage plans.

6.1.1. Deck layout

The structured layout of lashing points provides a matrix that can partly be seen in figure
4.

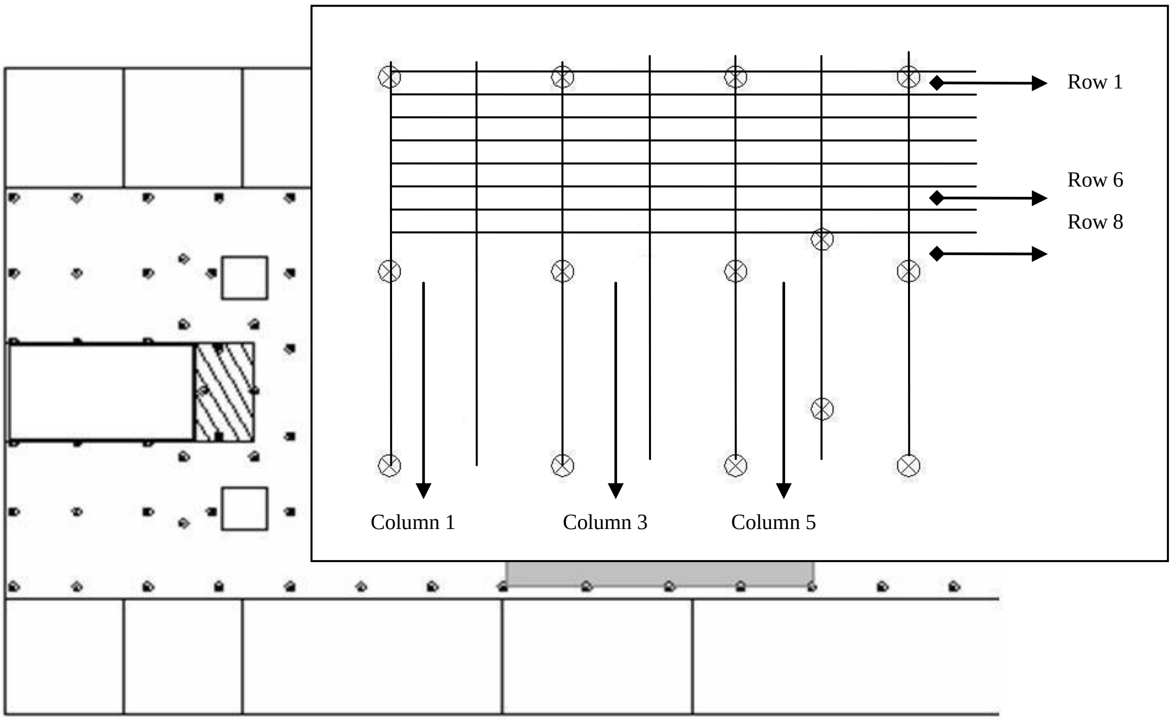


Figure 4: Matrix layout of main vehicle deck.

The use of matrices has several advantages:

- RoRo cargo can always be positioned between four lashing points.
- Free space can be allocated by simply blocking cells.
- The matrix layout can easily be developed for different types of ships.

6.1.2. Stowing requirements

Individuals sent to the DA hold genes that represent cargo and will be positioned into the stowage plan. Dimension and weight of the cargo will be looked up in the cargo list.

RoRo cargo will be stowed into the matrix one by one. A stowing example can be found in figure 5. RoRo cargo is stowed lane by lane, from back to front, starting at port side. The left figure shows a RoRo cargo that does not fit into the first lane anymore and therefore it will be placed in the next lane. The next RoRo cargo is smaller, but still fits in the first lane meaning that the free space will be filled up.

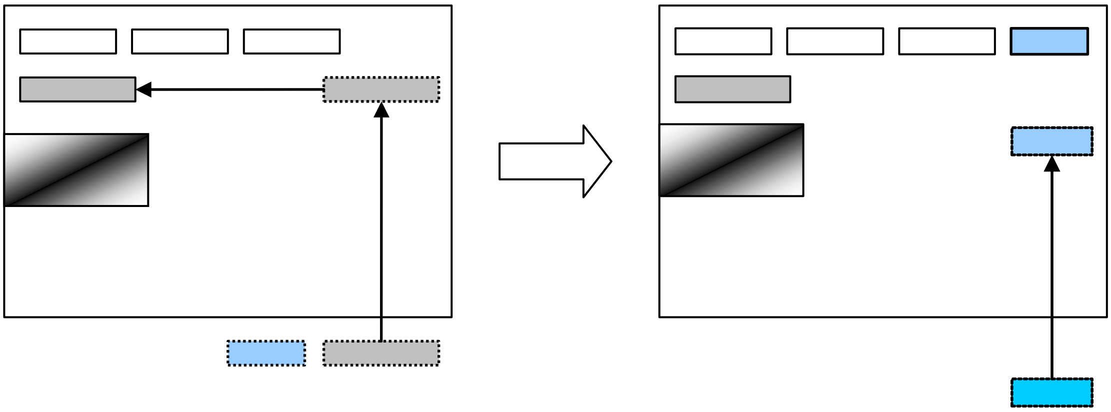


Figure 5: Stowing example 1.

When a deck is fully stowed or if a vehicle does not fit on the deck, the vehicle will be stowed onto the next deck. The stowing of RoRo cargo from port side to starboard can have a negative influence on safety requirements, especially when a ship is not fully loaded.

The stowing example in figure 6 is much more efficient. RoRo cargo is stowed from the outer lanes to the inner lanes in the directions of the dotted line. The area between the dotted line will be stowed at last after all other decks are fully stowed. By stowing in this way, free space in the middle of the ship is obtained, as much as possible, and cargo is spread over all decks. This will always provide free space for elevators and shifting of cargo when the ship is not fully loaded.

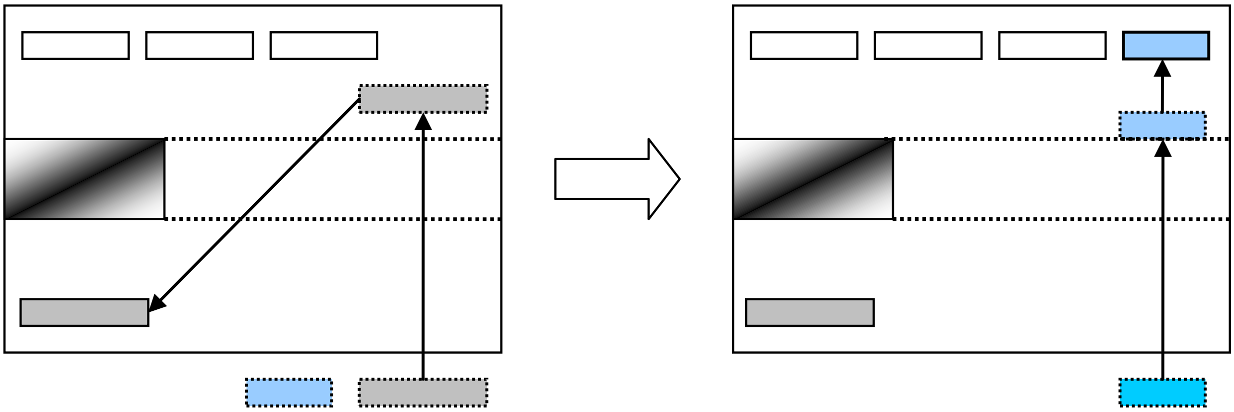


Figure 6: Stowing example 2.

The DA stows lane by lane. This gives the ability to control the design of the stowage plan to the user, by changing the sequence of the stow lanes. Free decks can be allocated by excluding a certain deck. A preference for a free deck can be obtained by stowing a certain deck at last.

The DA always develops feasible stowage plans according to the requirements specific to the ship. For example RoRo cargo above 25 ton will never be positioned on deck at the second level according to the maximum lift capacity, and helicopters will always be positioned in the hangar. In this way unfeasible stowage plans concerning the ship criteria will never be generated beforehand.

The sequence of genes of each particular individual does represent a unique stowage plan.

6.2. Evaluation algorithm

The EA calculates the fitness value of each unique stowage plan. In order to determine the fitness value, the fixed criteria and soft criteria are transposed into evaluation functions. The goal is to maximize the sum of the total value of the several evaluation functions.

$$\max\ F = \sum_{j=1}^{\substack{Amount\,of\\ subfunctions}} f_j(S_i)$$

Stowage plans are evaluated by rewarding ‘good’ stowage plans and penalizing ‘bad’ stowage plans. Values to criteria can be given by variation in rewards and penalties. The design of the stowage plan strongly depends on the settings of the evaluation functions. This will be displayed in the application example.

For this proof of concept following settings of the evaluation functions are given as an example:

f_1 (fixed criteria 1)

The metacentric height G’M must be greater than 0.2 meter; a penalty will be given if it is below 0.2 meter.

if (G’M <= 0.2 m) then $f_1 = -10000$ else $f_1 = 0$

f_2 (fixed criteria 2)

The evaluation of even loading is done by an interval of the angle of heel.

if (angle of heel <= 0.5 deg) then $f_2 = 200$
if (angle of heel > 0.5 deg) and (angle of heel <= 1 deg) then $f_2 = 100$
if (angle of heel > 1 deg) and (angle of heel <= 5 deg) then $f_2 = 0$
if (angle of heel > 5 deg) then $f_2 = -500$

f_3 (fixed criteria 3)
Evaluating trim is also done based on an interval.

if (abs(trim) <= 0.5 m) then $f_3 = 200$
if (abs(trim) > 0.5 m) and (abs(trim) <= 1 m) then $f_3 = 100$
if (abs(trim) > 1 m) and (abs(trim) <= 5 m) then $f_3 = 0$
if abs(trim) > 5 m then $f_3 = -100$

f_4 (soft criteria 1)
RoRo cargo with priority 1 is rewarded if it is positioned near ramp 1. The closer the cargo is positioned to the ramp the higher the reward will be. RoRo cargo with priority 2 is rewarded on the same way, but than for ramp 2.

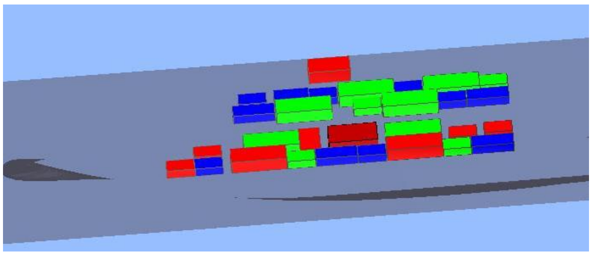
f_5 (soft criteria 3)
It is desirable to position RoRo cargo with a width larger than 2.3 meters at the outer lanes of the deck. Shifting will be difficult if RoRo cargo with these dimensions is placed at the centre of the ship. If RoRo cargo with a width larger than 2.3 meters is positioned in the outer lanes of the deck, the cargo will be rewarded.

f_6 (soft criteria 6)
The application must be protected for obtaining high fitness values, by not by positioning RoRo cargo from the cargo list on the ship. An irrevocable penalty will be given if this occurs. All RoRo cargo from the cargo list must be postioned on the stowage plan.

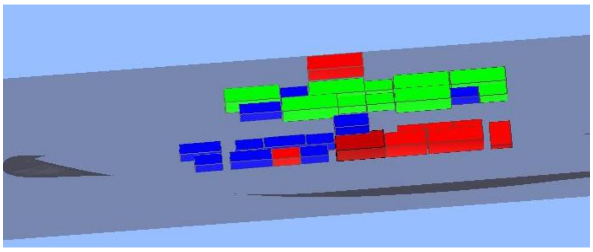
f_7 (soft criteria 7)
If standard equipment is positioned into the specified area it will be rewarded.

APPLICATION EXAMPLE

For the first application example a cargo list with 30 pieces of unequal RoRo cargo is loaded in the SPG. Graphical output can be found in figure 7 and figure 8.

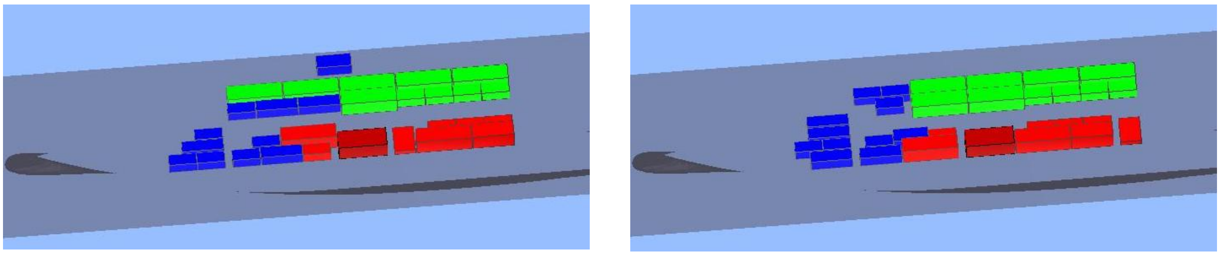


Initial population



After 2500 iterations

Figure 7: Graphical output.



After 7.500 iterations After 20.000 iterations

Figure 8: Graphical output.

RoRo cargo having a priority of disembarking must be positioned near ramp 1 or 2. Red blocks present RoRo cargo having priority 1 and green cargo have priority 2. After 20.000 iterations the SPG developed a stowage plan that complies with safety criteria, ship criteria and user criteria. In table 5 the fitness values of the above stowage plans are given. It can be seen that the fitness value of the stowage plan generated after 20.000 iterations is equal to the fitness value of the stowage plan generated after 200.000 iterations.

Table 5.

Iterations	Fitness value
1	956
2.500	1464
7.500	1535
20.000	1574
200.000	1574

Output of the SPG with a cargo list of 120 RoRo cargo's can be found in figure 9. All decks on both levels are now fully stowed.

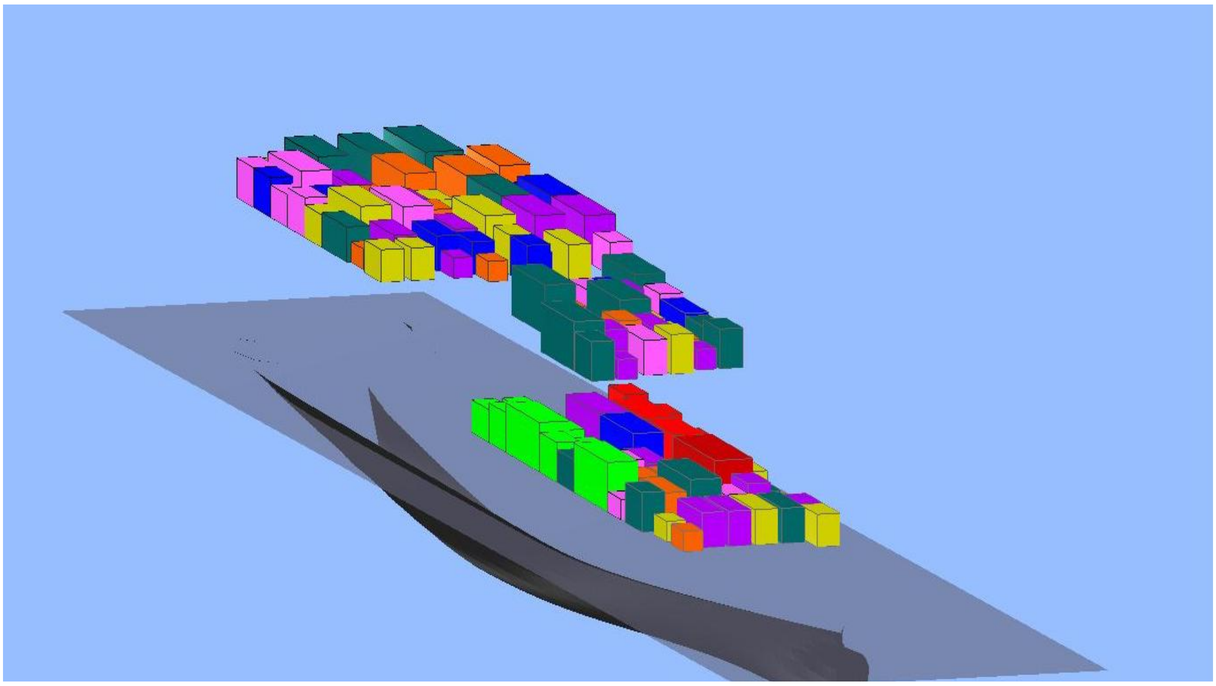


Figure 9: Graphical output

By variation in rewarding and penalizing, the user can give a twist to the design of the stowage plan. The following example demonstrates this feature. In figure 10 output of the program is shown.

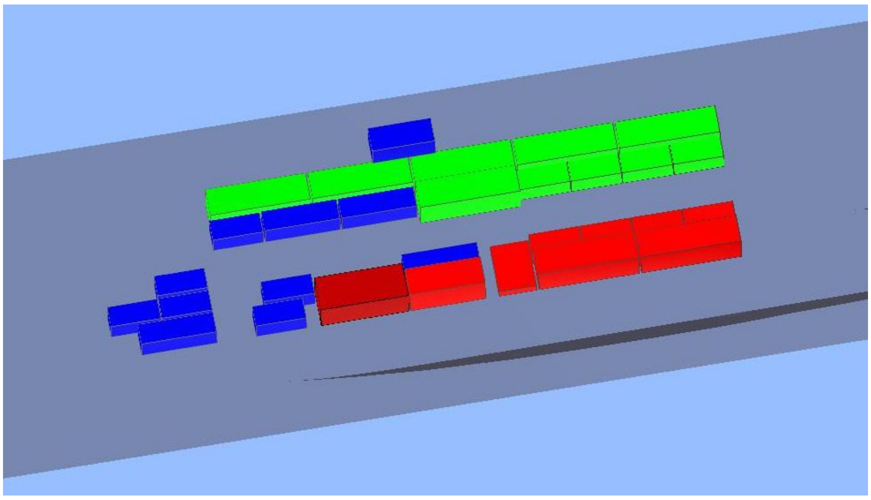


Figure 10: Graphical output

Evaluation of function 5 will be deleted and the generator runs again. Small RoRo cargo can now be placed in the outer lanes without affecting the fitness value. By positioning small RoRo cargo closer to the ramp than larger RoRo cargo, more RoRo cargo can be placed near the ramp and a higher fitness value is obtained. This is demonstrated in figure 11.

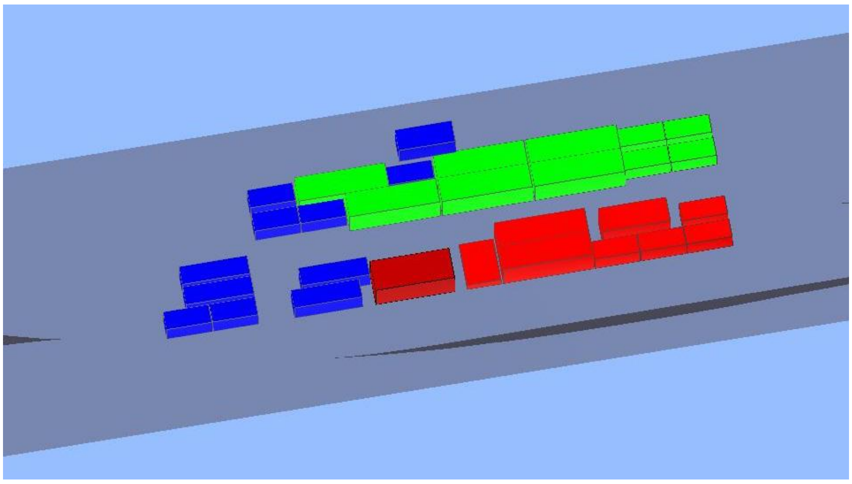


Figure 11: Graphical output

This method has proved the user friendly environment of the SPG. By editing, deleting or adding evaluation functions into the DA, the stowage plan can be edited.

The output of the SPG can also be edited in the computer loading software by hand after each generation. The amount of iterations needed to develop feasible stowage plans depends on the cargo list (amount of RoRo cargo, dimensions and weights) and the evaluation functions. Since the optimal fitness value is not known a priori, it is hard to set the optimum amount of iterations needed to develop feasible stowage plans.

Several tests have shown that after 200.000 iterations the SGP was not able to find higher fitness values, when the ship is fully loaded. Therefore for this proof of concept 200.000 iterations are chosen to be standard to develop stowage plans. Future research should investigate the amount of iterations needed. The SGP runs approximately one to three hours, depending on hardware performance.

CONCLUSION

The possibility to implement a stowage plan generator (SPG) for unequal RoRo cargo in a loading computer software has been shown by a proof of concept. The SPG is a combinatorial optimisation problem that can be solved with the help of a genetic algorithm. A design algorithm decodes each individual into a real stowage plan in order to enable the evaluation algorithm to determine its fitness value. After evaluation, the genetic algorithm appeared to be able to develop a feasible stowage plan by its evolutionary strength.

The advantages of an SPG have been proven since the required CPU calculation time is much less than designing stowage plans by hand, whilst the SPG assures that all safety, ship and user criteria are met to the maximum extent. Such a SPG has the potential to effectively assist all personnel involved in transporting equipment both onboard (e.g. stowage planner) and ashore (e.g. fleet command).
The successful use in practice of an SPG is fully dependent on the correct definition of all critical safety, ship and user criteria for all foreseen types of operational missions the ship will encounter throughout its life.

FUTURE RESEARCH

In this study a proof of concept for the automatic generation of feasible and optimal stowage plans is presented. Although the investigations conducted so far are still in a preliminary phase, the method appears to be quite attractive. In order to investigate its potential in practice a number of issues have to be investigated more thoroughly, for instance:

- The application of more innovative genetic algorithms.
- The number of iterations required to achieve a satisfactory result.
- All foreseen critical safety , ship and user criteria.
- Inclusion of non-RoRo cargo (like containers and ship fuel), and application of water ballast optimisation in order to balance or stabilize the vessel.
- Dynamic simulation of shifting of RoRo cargo in order to determine required time for e.g. embarking or disembarking, and to judge the available free space between all cargo items.

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