A new engineering & production approach in shipbuilding to eliminate manual cutting by use of large predetermined openings

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ABSTRACT
Western shipyards have to distinguish themselves by complex ships with short delivery times. This entails that in most cases the production already starts while the engineering has not even been finished. If the pipes and cables are not routed when the steel plate are cut by the CNC machine, the associated penetrations have to be cut manually during section building, which is very expensive.
The ideal situation is to know the location and size of all penetration before the plates are cut. However, this is not realistic in all cases and therefore a new engineering and production approach is devised. If the penetrations are not known on time, large openings are to be made which can later be filled with inserts, when all exact penetrations are known.
It is possible to just open a lot of large openings, or an estimation concerning optimal openings can be performed. In this research, several algorithms have been created to estimate an optimal opening for a certain penetration, and to check whether this penetration fits in the estimated opening. For the closing of the opening, several methods are described as well. An obvious choice is to close using a welded steel insert plate. A less obvious choice is the rather new product called NOFIRNO®. Both solutions have some advantages and disadvantages for different situations.
All the algorithms are validated by comparing the results to actual built vessels. With the accurateness of this validation, a business case has been performed for several opening methods, combined with several closing methods. The final conclusions and recommendations are not unambiguous for each situation.

1. INTRODUCTION

1.1. Background

An essential part of ship building is the piping & machinery. A vessel contains an enormous amount of pipes that have to be routed to connect the equipment to each other. Most of these pipes are routed through structural elements like decks, bulkheads and profiles. These passages then need penetrations. If the penetrations are known on time, they can directly be cut with the CNC plasma machine, which is very cheap.

If the positions of the penetrations are not known on time and thereby not present on the cutting drawing, they have to be cut manually which can cost up to 1000 euros per hole. This is the case if equipment information is not available on time, mainly due to mutual dependencies and deteriorating communication. This information includes 3D models with the size and position of connections. If this information is not available, the piping cannot be routed in detail, then the exact locations of penetrations are not known and therefore not cut during machine cutting.

This issue was subject to a dedicated research and findings were published in the master thesis with title *Reducing pipe penetration costs in shipbuilding*. This paper summarises the contents of aforementioned thesis.

1.2. Research Objective

The final objective of the research project was to devise a method by which pipe penetrations in TSHD's can be sized and located before the detailed pipe routing is known. Then the holes can be cut by the CNC cutting machine instead of manually. If this method is devised, it had to be determined whether it is more cost efficient compared to the current situation.

In order to arrive at this new method, several sub-questions are answered in advance. First the method must follow the set rules, both by the classification societies and the company. Besides, a lot of information had to be achieved regarding the relevant production costs concerning cutting and pipe manufacturing. Also the relevant ship systems and its interconnections were broadly investigated, to get a good insight about several required penetrations.

At the end, the aim of this research is to minimize the combination of piping- and penetration costs:

Minimize
$$C = C_E + C_{PM} + C_O + C_{HC}$$

Equation 1 Piping- and penetration costs

The total costs (C) consist of the total engineering costs (C_E), the total pipe manufacturing costs (C_{PM}), the total outfitting costs (C_O) and the total hole cutting costs (C_{HC}).

1.3. Hole Cutting Costs

Holes for penetrations can be cut by CNC machine or by hand. Cutting by CNC machine is always preferred due to precision, speed, safety and costs. However, when structural members are already attached, CNC cutting is not possible any more. Then manual cutting must be applied which involves additional costs and man-hours due to several tasks like:

- Work division
- Drawing printing
- Set up of equipment
- Building of scaffolding
- Measuring and marking
- Finishing
- Additional painting

With the CNC machine, the cut of a common hole costs about 1 euro. For manually cutting, it will cost over 180 euro during section building, and between 500-1000 during slipway building.

1.4. Solution Approaches

There are several approaches to deal with the problem. Three are discussed:

1. **An improved process** in which all machinery locations and dimensions are known on time.
2. **A different engineering approach** in which the piping is routed towards predetermined holes, instead of holes that are cut around the piping.
3. **A different planning** where the production only starts when all required holes are defined.

Only the second approach is feasible for this research. The first approach is about improving the process. Therefore especially the communication between departments must be improved and accelerated. Due to more and more outsourcing abroad, this will be very difficult in the future. The third approach is not feasible because a longer lead time is not an option for Royal IHC due to its unique selling point of fast delivery. Besides, there will be not enough time and resources available to test a totally new planning approach. The second approach, a new engineering approach, can be well investigated and evaluated during the research, due to the availability of required resources as stakeholders and registered data.

2. METHOD PRINCIPLES

2.1. Systems and Locations

To keep the research feasible, the case study is performed for a small part of a ship type with much registered information available. For the case, the penetrations through the piping and cabling trunk in the accommodation of TSHDs are studied. The trunk is a shaft over multiple decks for the transportation of pipes and cables. The main systems within this trunk are water systems, HVAC and cabling. There are mainly two possible approaches to deal with this penetrations:

1. To estimate the exact location of a certain penetration.
2. To estimate the approximate location of all penetrations and estimate large openings.

It would be very beneficial if the exact penetration locations can be estimated before the total routing is finished. However, especially for high density location as the trunk this will be very difficult due to the high density of pipes and small possibility for adjustments. If for example in the end two penetrations need to be swapped, it can cause large problems when the pipes cannot pass each other inside the trunk.

2.2. Opening Methods

Because the exact locations and sizes of penetrations are too difficult to estimate on beforehand, another method is needed. It is possible to make large openings in the trunk initially, so that the cutting and building can start, and later fill this openings with an insert when the exact penetrations are known.

To maintain the most freedom of routing, these openings are to be kept as large as possible. A common trunk of Royal IHC built ships consists of vertical plates with vertical profiles with a general distance in between of around 700mm. There are horizontal plates for each deck with a ceiling beneath. The constraints as shown in Figure 1 are the upper deck (clearance: 100mm), the profiles next to it (clearance: 100mm) and de ceiling below (clearance: 0mm).

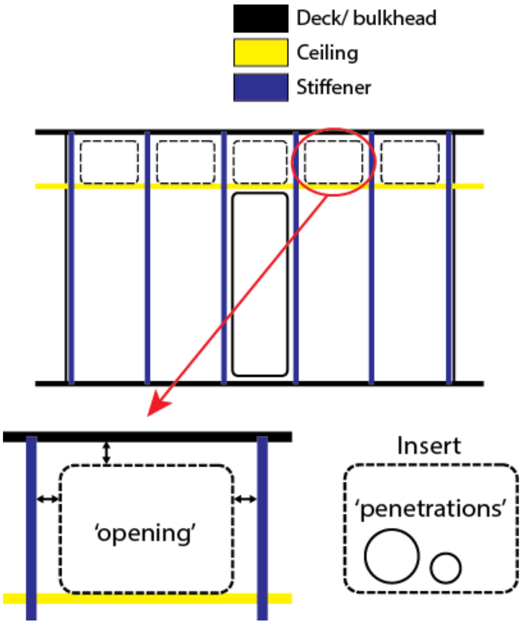

Figure 1 Schematic representation of trunk with possible openings

Now it is clear where the openings can be placed and of which size, it has to be determined which openings should really be opened. In general, three different concepts can be distinguished:

1. **Open all the openings** and later close them all with inserts. This implies there probably will be openings without any penetration and they just have to be closed with inserts.
2. Estimate where the penetrations will be and **open the openings with expected penetrations.** This implies that there may be wrong estimations and penetrations turn out to be at a position where no opening is. Then still a hole has to be cut manually. It is also possible that openings were estimated incorrect and needs to be closed with inserts.
3. Estimate where the penetrations will be and **open the openings with expected penetrations.** When a penetrations is assumed to be sure, and there are no other unsure penetrations in this opening, cut this hole exactly. This penetrations is then fixed and assumption/ exchanges are barely possible. It is also possible that an opening is estimated incorrect and needs to be closed with an insert.

The third method seems to be the most advanced and beneficial one, because of the least closing work and still large freedom of routing. However, it is dependent on the estimation usability whether this method can really work. If the estimation is really accurate to the current situation, this method will work. If this is not the case, it will involve even more problems due to adjust- and repair work.

2.3. Closing Methods

In section 2.2, several methods regarding the opening were discussed. For the closing of the openings there are some different options as well. In this section, the advantages and disadvantages of two possible solutions are described and discussed.

1. Steel plate cut by CNC cutting machine and manually welded in the structure.
2. NOFIRNO® solution by Beele Engineering BV.

2.3.1. Steel Welded Plate

Using a steel welded plate would be the most obvious choice, because it is currently applied multiple times at Royal IHC. All the required resources like material, techniques and knowledge is already available by the company. The steel plate can be cut by the automatic CNC plasma machine which is very cheap, fast and accurate. Then the complete insert plate including penetrations can be welded into the construction. If other welding is required at the same location at about the same moment, this additional welding does not take a lot of effort; no measuring has to be done.

2.3.2. NOFIRNO®

NOFIRNO® is one of the transit solutions by Beele Engineering, located in Aalten, the Netherlands. It is designed especially for watertight and fire resistant penetrations. With this method, the pipe is put through the transit. Then rubber sleeves are put around and it is covered with a fire- and waterproof sealant, as can be seen in Figure 2.

Figure 2 Creating a fire- and waterproof transit with NOFIRNO® sleeves and sealant

2.3.3. Comparison

Both the methods are able to meet the requirements of watertightness, fire resistance and strength. The implementation for the “steel welded plate” method can be very fast at low costs and without much effort. NOFIRNO® is more expensive, but it offers some benefits as well. For the creation of the NOFIRNO® transit there is no heat involved, which makes it possible to apply at an late building stage, even at the quay. Besides, the rubber absorbs motion which can result in less vibrations, fatigue and noise. Finally, the addition of extra penetration is very fast and cheap with NOFIRNO®

2.4. Estimation Methods

In section 2.2 and 2.3, the concepts for opening and closing are described. As was argued in this section, for the concept of inserts to work well, it is important that there is logic available to pick ‘the right openings’, as this will highly contribute to the success of the method. To make sure that the right openings are opened as much as possible, an estimation method with the right functional requirements has to be established. First the overall flow for the estimation is discussed. Then the two algorithms that are used for this estimation are elaborated.

In Figure 3, the total flow diagram is shown that can be used if the approach with using inserts is applied. This diagram can be described in the following 7 steps:

1. **Determine trunk dimensions**
   First the dimensions of the trunk are received from the construction plan. This is the starting point of the flow.
2. **Determine where openings are possible**
   With the dimensions of the trunk, the deck and ceiling heights and the other positions of obstacles like profiles and doors, are known.
3. **Estimate where systems will penetrate the trunk**
   On the basis of arrangements and the equipment on system diagrams, an estimation is done using an algorithm, which will be discussed in 2.4.1.
4. **Choose optimal next opening**
   If the penetrations doesn’t fit in the estimated opening, the next best opening will be chosen. To check whether the penetrations fit, another algorithm is used, described in 2.4.2.
5. **Determine which openings need to be opened**
   When all penetrations are estimated and appointed to a certain opening, it can easily be seen which openings should be opened and which ones can remain closed.
6. **Cut out only hole for penetrations in these openings**
   If an opening contains only 100% sure penetrations, just the penetrations should be cut out, and not the whole opening.
7. **Cut out whole opening**
   If there is at least one unsure penetrations, the whole opening has to be cut out.

Now all the construction plates can be cut and the section building can start.

In Figure 3, two yellow flag boxes with red outline are indicating the two algorithms that are used for the estimation. First there is the algorithm to estimate which opening is preferred for each penetration. Then there is an algorithm to check whether this penetration fits in this opening, together with previous appointed ones. These algorithms will be explained in next sections.

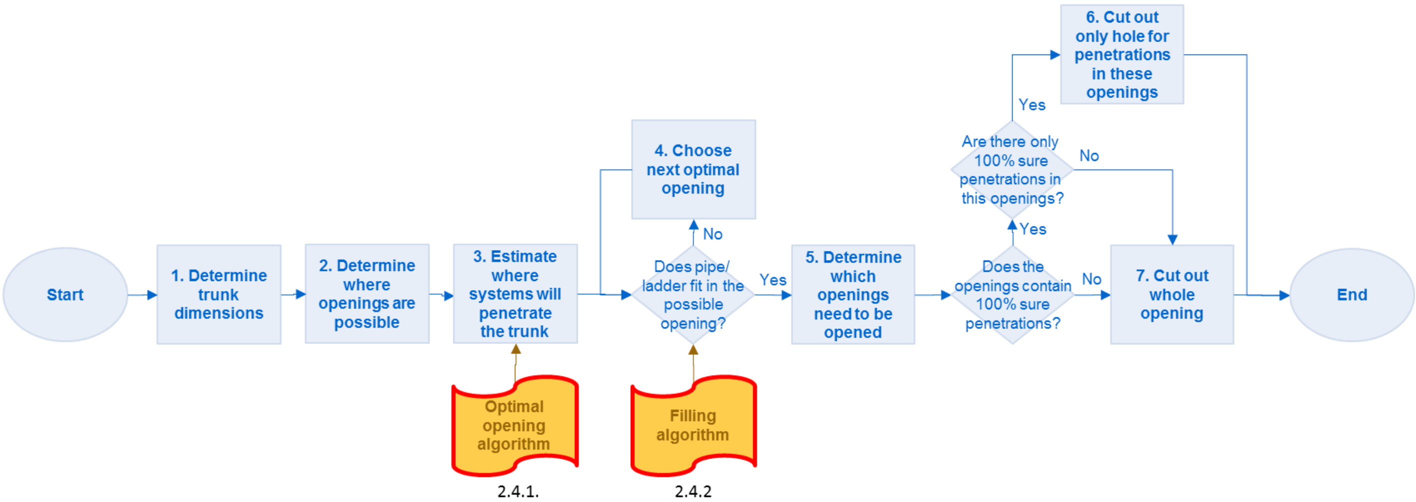

Figure 3 Algorithm flow diagram

2.4.1. Optimal Opening Estimation Algorithm

The optimal opening estimation algorithm chooses the best opening of the earlier defined possible openings in the trunk. It does not define an exact location inside this opening, to keep the freedom as large as possible for the router. The estimation method for the location of penetrations is not equal for all systems in the trunk. A division is made between cabling, water (grey, black, potable) and HVAC (supply, exhaust, recirculation). The algorithm will use the same sequence as the systems are routed in reality:

1. Cabling
2. Grey water
3. Black water
4. HVAC
5. Hot & cold potable water

2.4.1.1. Cabling

Because of the very early stage the cabling penetrations are determined, and the lack of consistency between different ships, these penetrations are considered to be known in the estimation model. Therefore the cabling penetrations are placed at the start in the known opening at the highest point, because cabling always must be routed as high as possible. (Bureau Veritas - Steelships, Pt C)

2.4.1.2. Water

For the water systems there are some important characteristic. Water lines are connected to all sanitary-, galley- and laundry equipment. All this locations that have to be reached in a system will be called 'equipment' from now. First the pipes are to be bundled inside or outside the trunk. Bundling inside can result in less pipe length, but it is often impossible due to the high density of piping inside the trunk. Besides, water lines require to remain as short as possible, due to descending pipes and the drainage of disposals. Therefore a "A* shortest path" algorithm is used (Pathfinding using A*, 2017).

The inputs for the water systems algorithm are:

- "Equipment" locations: toilets, showers, sinks, washing machine etc.
- Bundled inside or outside trunk

To get the opening with the lowest extreme length to all the equipment, the defined algorithm steps are:

1. Find lengths of orthogonal shortest paths between all equipment (A,B,…N) and all openings (1,2,…N).
2. Determine extreme value of the lengths from step 1 for each opening.

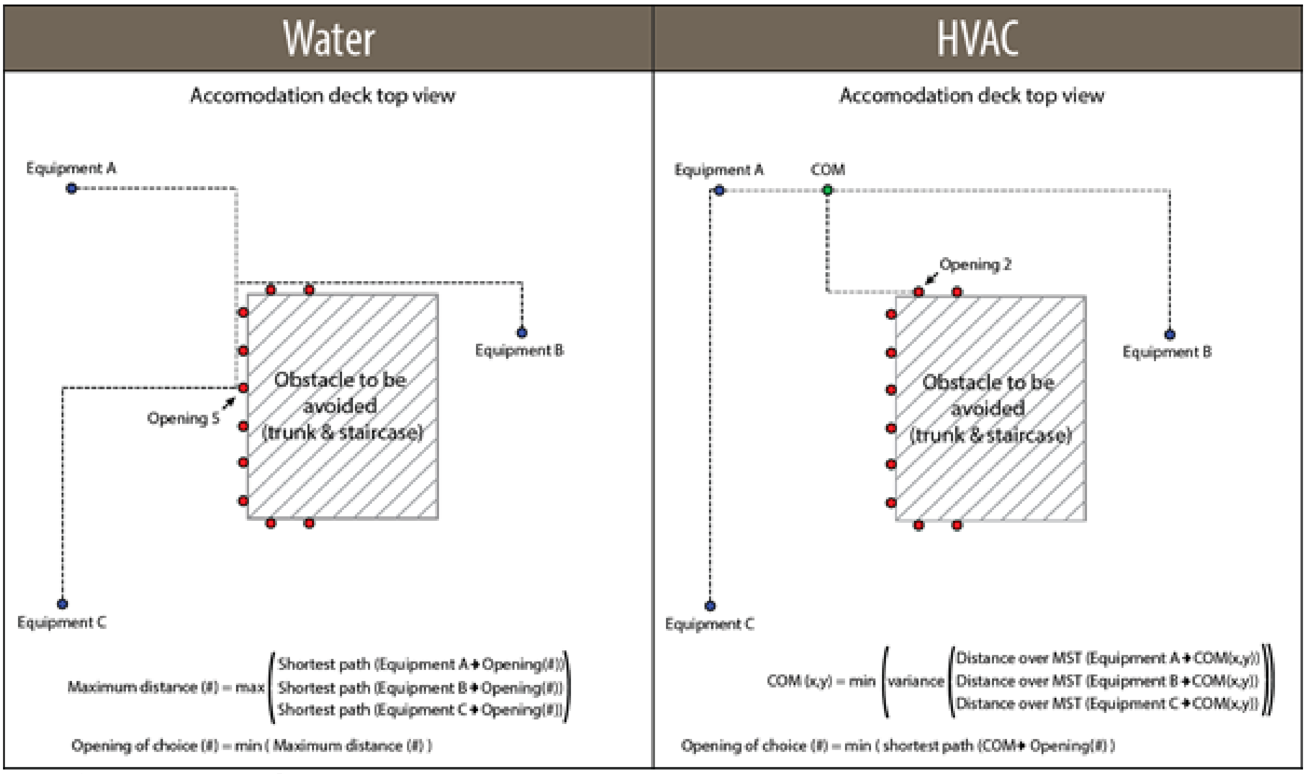

Figure 4 Optimal opening estimation algorithms

3. Determine opening with the lowest extreme value of the length.
4. Opening is the optimal opening.

On the left side of Figure 4, a visualization of the optimal opening estimation algorithm for water systems is shown. The red dots refer to possible trunk openings, the blue dots to equipment locations. The hatched rectangle indicates the trunk and the staircase. (there are no penetrations possible between trunk and staircase)

2.4.1.3. HVAC

For the HVAC optimal opening estimation, another method has to be used. Water has simply other characteristics than air. Because of pressure drops, air pipes should not be made too long. Besides, a good distribution over the equipment (for example AC units) is required.

First the algorithm connects all equipment with the ''minimum spanning tree algorithm'' by Prim (Prim's Algorithm, 2017). Then the point on this tree with the shortest *index run* has to be found. The index run is the run from the fan to the unit with the highest pressure drop (Kharagpur, 2014). With the algorithm the shortest index run is calculated. That can be reached by calculating the point that has the lowest variance of the distances between this point and all the equipment. This point is now called "COM". The last step is to find the minimum shortest path between COM and the red dots. The result will be the ''opening of choice''. Again the input is:

- "Equipment" locations: AC units, toilets, etc.

The defined algorithm steps are:

1. Find minimum spanning tree between all equipment (A,B,…N) with Prim's MST algorithm.
2. Determine lengths between each point on the MST and the all equipment (A,B,…N), measured over the MST path.
3. Determine point on the MST path with the lowest variance of lengths from step 2.
4. Determine shortest path between the point from step 3 and all openings (1,2,…N).
5. Determine the opening with the lowest shortest path from step 4.
6. This opening is the optimal opening.

2.4.2. Filling Algorithm

When for a certain system the estimation is done for the optimal opening, is has to be checked whether this penetration fits. This is done by a second algorithm. The functional aspect of this algorithm is to check whether the penetration fits in the opening, regarding the size of the opening and the other penetrations. The technical way to check this, is to fill up a rectangle (the opening) with blocks (penetrations) and check whether these blocks fit within the rectangle without overlapping each other.

The inputs for this algorithm are:

- Possible trunk openings (number and dimensions)
- Penetration dimension : L x H = (1.5D) x (1.5D)
- Estimated optimal opening from first algorithm.

Then the following steps are to be taken by the algorithm:

1. Plot trunk lay-out with all possible openings (1,2,…N).
2. Plot penetration with given dimensions as a rectangle inside the opening followed from the estimation algorithm. (Fill cabling from the left top corner, others from the left bottom corner. The sequence is described in 2.4.1.)
3. Determine whether the rectangle fits inside the opening, without overlapping the borders or other penetration rectangles.
4. If yes, plot the rectangle inside the opening.
5. If no, plot the rectangle on the next row and go back to step 3.
6. If the rectangle keeps overlapping the border or other rectangles, ask the user for a new optimal opening. (preferably optimal+1 or optimal-1)

The holes are filled with the sequence as it is routed. (Figure 5) The cable ladders are filled from the top left corner. All electricity is preferred to be routed above other (water) systems. All the other systems are filled from the bottom left corner, always in the right sequence. This keeps the grey water penetration as low as possible. The filling first works horizontally. When another penetration does not fit on the same row, it shifts to the next

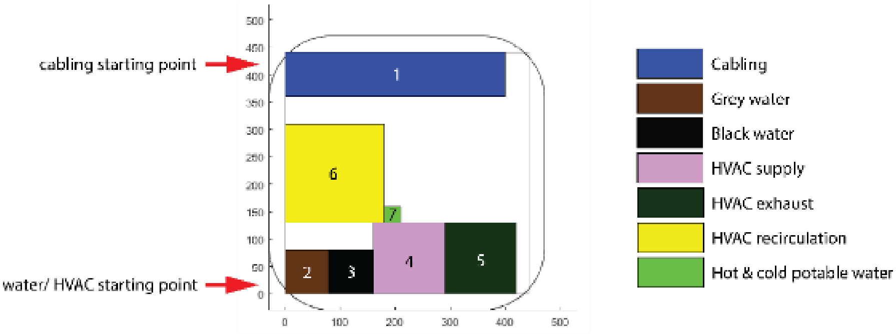

Figure 5 Filling algorithm with sequence

row. As can be seen in Figure 5, the row is ''as high as the highest rectangle''. This has as a positive consequence that at the end all penetrations of a row are allowed to be shifted mutually.

When at a point a next penetration does not fit in the estimated opening, the software displays an error message that says another opening has to be picked. Then the user manually chooses another opening. This is because the user has engineering experience and he can apply his knowledge to his decision. For example, he can see whether there is another penetration of the same system in a nearby opening so that they can be bundled. He can also prefer to put it in an opening where already other penetrations are present so that others can remain closed. The program then checks whether the penetration fits in this opening of choice.

Summarizing, the first algorithm estimates the optimal opening for a penetration. The second algorithm checks whether this fits. If this is not the case, the second best opening is chosen. Then, in the end and overview of the openings with penetrations is created and it can be seen which openings must be opened. As mentioned before, not the exact position of the penetration is estimated, only the opening where it should go through.

3. VALIDATION

In this chapter, the correctness and usability of the algorithms are determined. For 4 recently built IHC vessels, the algorithms have estimated which trunk openings should be opened and which ones could remain closed. These results are then compared to the actually built vessels. In Figure 6, an example of a plot of the optimal opening estimation algorithm is shown for water (left) and HVAC (right). It indicates a top view of a deck and the trunk with possible openings in the center. Figure 7 is a

composition of the trunk openings filled with penetrations.

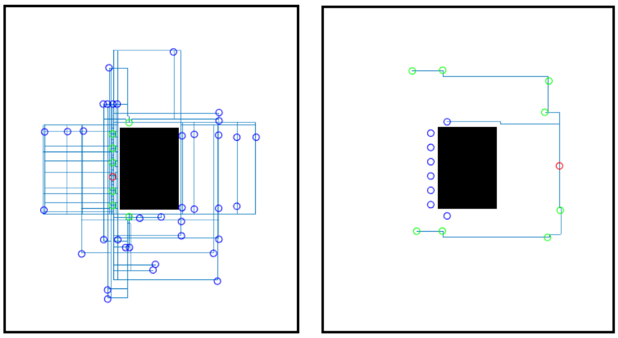

Figure 6 Optimal opening estimation algorithm

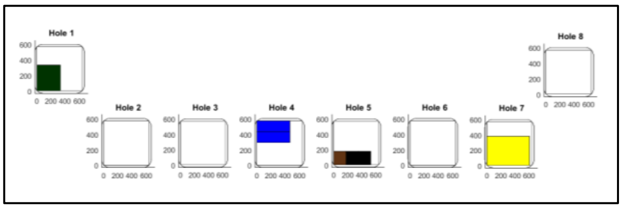

Figure 7 Filling algorithm composition of a deck

These compositions are compared to the reality. The result at the end contains the estimated opening for all penetrations. With this information, several comparisons can be performed.

First for each separate penetration, the difference is determined between the opening that is estimated by the algorithm and the opening that is actually used in the real built ship. When for example the algorithm gives 'opening 4' as an optimal and the pipe is actually routed through 'opening 3', the difference is 1. This can be summed for all decks of a ship.

	Ship 1	Ship 2	Ship 3	Ship 4	Average	Min.	Max.
Correctly estimated opening	88%	88%	97%	81%	89%	81%	97%
Opened opening	79%	81%	82%	82%	81%	79%	82%
Opening to be added	11%	19%	9%	14%	13%	9%	19%
Opening to be closed	10%	0%	9%	4%	6%	0%	10%

Table 1 Difference between algorithm and real built ships

Another comparison that is investigated, is the difference between the openings that are used in real and the openings that should be opened according the algorithm. This gives for example the result that opening 1-2-4-5-8 are used in real and opening 1-3-4-5-7 are opened according the algorithm. If the estimated opening is not equal to the real opening, in most cases it differs only by 1. It is decided that a difference of only 1 is still acceptable, because in reality this opening could have been used as well.

Table 1 gives a general impression about the correctness of the algorithm. It shows the difference between the estimated optimal opening and the real used opening for each penetration. However, it will be more interesting to know the correctness of the opened openings. If there is an opening too little or too many, an opening has to be added or closed respectively. A clear overview of these percentages is shown Table 1 as well. The lower three rows say more about the actual impact, because that values are about the estimated and real opened openings. Then it does not matter that much which penetration is passing through a certain opening.

4. EVALUATION

As described in chapter 2, three different opening methods are compared to the current situation at Royal IHC, for the two different closing methods. (Table 2) Therefore first the costs of several possible transits are calculated. Then the total transit costs of an accommodation trunk in a ship is calculated.

	Current state	Open all openings	Open estimated openings	10% sure, others estimated
Manual cutting	X			
Steel insert plate		X	X	X
NOFIRNO®		X	X	X

Table 2 Solution matrix

4.1. Transit Costs

In total there are three transit methods that are compared:

- Manual cutting: Manually cut the exact holes for the penetrations when the dimensions are known.
- Welded steel plate: Automatically cut the large openings and fill them with the steel plates.
- NOFIRNO®: Automatically cut the large openings and fill them with the NOFIRNO® sleeves and sealant.

For these three transit methods it is calculated how much a normal transit with penetrations, an added transit with penetrations and a closed transit will cost approximately. The results for a total average trunk are shown in Table 3.

Now there is a clear overview of the purchase- and production costs for several transit methods. When all possible openings are opened and then closed, the welded steel method will give a cost reduction of 9%. This seems to be a small number, but it also can make the engineering process a lot less complex.

	Current state	**Open all openings**		**Open estimated openings**		**10% sure, others estimated**		
	Manual cutting	*Welded steel plate*	*NOFIRNO*	*Welded steel plate*	*NOFIRNO*	*Manual cutting*	*Welded steel plate*	*NOFIRNO*
Normal penetration	€ 8.869,45	€ 6.694,20	€ 20.524,41	€ 5.637,22	€ 17.283,72	€ 7.982,50	€ 5.073,50	€ 15.555,35
Adding opening	-	-	-	€ 1.056,98	€ 3.240,70	-	€ 951,28	€ 2.916,63
Closing opening	-	€ 1.371,67	€ 18.135,42	€ 352,33	€ 1.080,23	-	€ 317,09	€ 972,21
Total	**€ 8.9K**	**€ 8.1K**	**€ 38.7K**	**€ 7.0K**	**€ 21.6K**	**€ 8.0K**	**€ 6.3K**	**€ 19.4K**
Percentage*	**100%**	**91%**	**436%**	**79%**	**244%**	**100%**	**79%**	**244%**

Table 3 Total trunk transit costs comparison

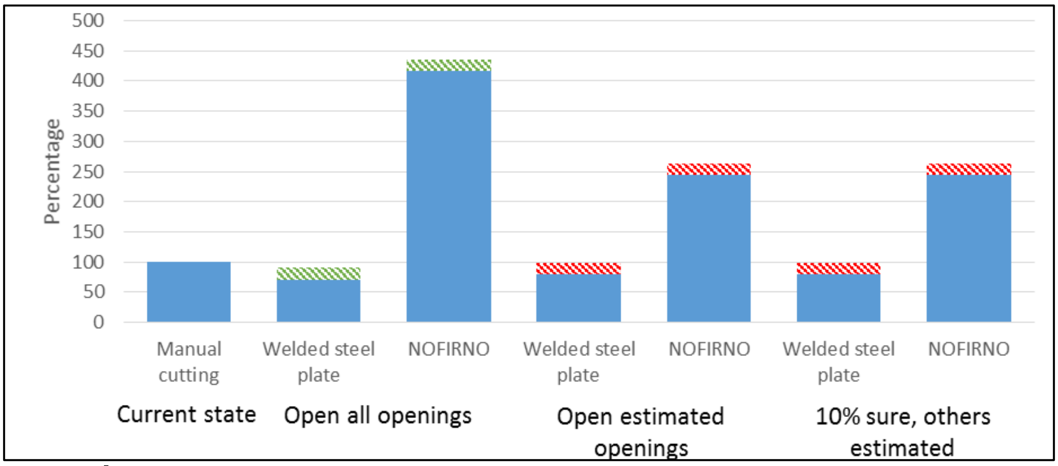

Figure 8 Trunk transit costs comparison

At the moment it is not possible to put an quantitative value to the decreasing engineering costs. Less work and communication is required, because the structural engineer can place all openings without input from the routing engineer. The NOFIRNO method will costs much more. However, this comparison is based on purchase and production costs. As stated before, NOFIRNO has some really big advantages in the field of safety and adaptability. This could reduce the engineering- and operational costs of the vessel. The exact reduction is hard to calculate and should be experienced with a real built ship. When only the estimated openings are opened and then closed with a steel welded plate, there will be a cost reduction of 21%. However, the implementation of and working with the algorithm will involve more complexity for the engineering department. This increasing or reducing engineering complexity is qualitatively shown in Figure 8. The green and red blocks indicate probable decreasing and increasing engineering costs respectively.

4.2. Effort-Benefit Analysis

The advantages and disadvantages of all concepts are broadly discussed. This can be converted to “benefits”. However, not all concepts are as easy to implemented in the existing process. In Figure 9, the four main concepts are qualitatively visualized in an Effort-Benefit matrix. Especially the mutual relation between the concepts are of interest, not the exact position. As can be seen, a steel welded plate involves less effort as the implementation of a new product, NOFIRNO. Besides, using an algorithm entails even higher effort due to the development, examination and training regarding the software.

The implementation of an algorithm will involve work on the IT department, first for implementation and later for support. Also the work for the routing engineers changes, but if the software is programmed and designed on a high level, this does not need to result in a lot of difficulties. It must be ensured that the routing engineer remain responsible for the routing and not the algorithm or IT engineer, which demands strict control. When NOFIRNO® is introduced, the work for the routing and structural engineers will become less complex and time pressurized, due to high dimension tolerance and late possible building phases. For the welders and outfitters, the work will change. Workers have to follow a training in the field of NOFIRNO® transits. However, the welding work and the transit production time are probably reduced.

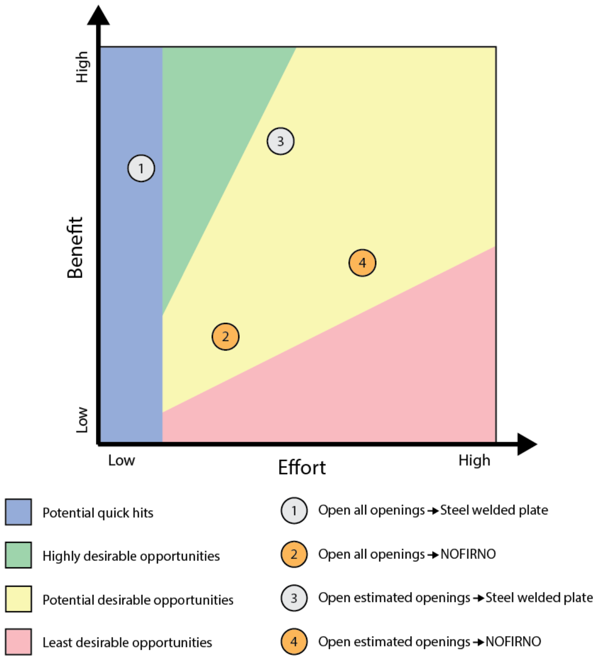

Figure 9 Effort-benefit analysis

5. DISCUSSION

In this chapter, first a conclusion is drawn about the best concept(s) for different situations. Then a further look is taken into the suitability of the concept in other ship- types and areas. Finally, some recommendation are made concerning the future for Royal IHC.

5.1. Conclusion

In chapter 4.1, the several opening and closing concepts are compared to each other on costs. It is clearly shown that for all proposed variants, using a steel insert plate for the closure successfully reduces the costs. However, it is important to keep in mind that for the problem location definition of this case study only two ships could be investigated, and for the algorithm validation only four ships. Besides, it is shown that the NOFIRNO transit will result in (much) higher costs. However, this comparison is about the purchase and production costs and does not say anything about the costs during operation and possible cost reductions in other areas.

When the “steel insert plate” concept is used, there is a cost reduction of 9% when all openings will be opened, and 21% when the algorithm is used. When all openings are opened, there is a large reduction of complexity. The engineer does not have to work with an algorithm and can just create the openings at a very early stage. There is very little information from other departments required. A lot of organizational activities will erase.

When the algorithm is used, the cost reduction for purchasing and production is higher. However, then the algorithm has to be further developed in the field of usability and performance testing. This will entail costs in the initial phase.

The research objective is stated in Equation 1. With the implementation of the new approach, using steel insert plates, these total piping and hole cutting costs will change. First of all the hole cutting costs (C_HC) will decrease, because the expensive manual cutting is reduced. Besides, the total engineering costs (C_E) will decrease as well. Pipe routing engineers know where the large openings are and can route the pipe through, without communicating and checking new required holes. The piping manufacturing costs (C_PM) will not differ a lot. The routing engineers are somewhat bound to the predetermined openings, but due to the extended time available for adjustments, the routing could even be more optimized regarding cost efficiency. Finally the outfitting costs (C_O) probably will not change. Just as with the manual cutting, the holes are not known very early and therefore pre-outfitting will be difficult. However, due to the large openings it is possible to already put the pipe spools approximately in the right area. Summarizing, the following changes for the new approach will be achieved:

$$C_{E,CS} > C_{E,FS}$$

$$C_{PM,CS} \sim C_{PM,FS}$$

$$C_{O,CS} \sim C_{O,FS}$$

$$C_{HC,CS} > C_{HC,FS}$$

Then:

$$C_{E,CS} + C_{PM,CS} + C_{O,CS} + C_{HC,CS} > C_{E,FS} + C_{PM,FS} + C_{O,FS} + C_{HC,FS}$$

$$C_{CS} > C_{FS}$$

CS and FS indicate the current state and future state respectively.

5.2. Expansion

It will be recommended to first test the approach for the researched location in this thesis. Then if the costs of the trunk actually decrease, the approach can be extended to other ship types and areas. Therefore the benefits of this approach should also apply for these extended types and areas.

First of all, an easy expansion can be made towards the same location on other custom-built ships like CSDs and PLVs, because the accommodation is rather equal. Besides, an expansion towards other locations with approximately the same requirements can be made. Some examples are given in Table 4.

	Engine room	Pump room	Tech. space	Switchb. room
Not all penetrations known on time	+	+	++	+
Lots of equipment	++	+	+	+
Many pipes/ cables bundled	++	+	+	++
Fire resistant	+	+	+	+
Watertight	+	+	+	+
Vibrations	++	+	+	-
Low strength limitations	-	-	-	-

Table 4 Other possible location

5.3. Recommendations

This research has shown that an intermediate solution, between the ideal all-known situation and the manually cutting situation, can be beneficial. In the ideal situation, all penetrations are known on time and no repair work is required. However, this ideal situation is not realistic mainly due to time pressure.

According to the results from this research, Royal IHC should implement the new approach for the cases that penetrations are not known for sure on time. However, it is important to keep in mind that due to lack of information the calculated repair costs are only based on two ships, and the algorithm results on only 4 ships. For a more convincing result, during the coming year(s), the approach including algorithm can be examined for the new built ships as well.

First a trial can be done for a small part of the vessel. This will not be of a large impact, because all the required knowledge and resources concerning the new approach are already available. If this is successful, it can easily be extended. Then, if stakeholders are convinced, a further look could be taken into the algorithm. It can be optimized by adding more constraints like the bundling of pipes and a certain descending characteristic. Also the interface and user friendliness have to be improved in order to keep it clear and easy for the engineers. In addition, the experienced routers and structural engineer have to give their opinion about the results of the algorithm and which aspect can be improved.

Because of custom-built shipbuilding, the exact situation is not always the same. Therefore, there is no unambiguous recommendation for all situations. A division is made between three situations:

- **Ideal situation**: Cut all holes by CNC plasma machine if they are sure.
- **During section building**: First open all openings and close with steel insert plate, later use estimation.
- **During slipway building**: First open all openings and close used openings with NOFIRNO® and unused openings with steel insert plate if possible, later use estimation.

If penetrations are known for sure, it is always best to cut them exactly by the CNC cutting machine. If a penetration is not known for sure, another approach is required. In the first instance, all possible openings will be opened. During section building, these openings should be closed with steel insert plates. This method can easily be tested without large adjustments or investments. All the material, techniques and other resources are already available within the company. During slipway building, these openings should be closed with NOFIRNO®. During section building, the costs for all closing concepts will not differ that much anymore. Then the additional advantages when using NOFIRNO® makes the decision. This includes the possibility of adding penetrations without heat, no centering required and the possibility of pre-outfitting. By using NOFIRNO® both CO and CE will decrease, but it CHC will increase. Then it has to be determined whether $\Delta CHC < \Delta CO + \Delta CE$.

In this case study, the cabling penetrations were considered to be known. The cabling penetrations are dependent on the placement of the vertical cable ladders, and that is dependent on the arrangement of the converter room. Because of the high variety of this converter room arrangements and possible design solution, cabling does not fit very well for an automatic algorithm. However, it is remarkable that different engineers will choose different design solutions, because cabling has the priority and therefore not much constraints. In the future it is recommended to create a standard or design rule regarding these cable ladders, in order to create more consistency.

In this research, a lot of innovative advantages of the NOFIRNO transit have emerged. Despite the higher purchasing costs, it seems to be a very good solution for the future. Currently the inventor of NOFIRNO, Beele Engineering B.V., tries to prove that most of contemporary transits are not as fire proof as it is said. Some large players like Hyundai, the Royal Navy and the US Navy are already convinced of the product. Because of the novelty of the product, there is not much known about the costs on the long term. In a few years, more information and proof might be available. Then it could be a really interesting solution for IHC. It will take away a lot complexity to the watertight and fire proof transits. Repair work for the addition of holes will be reduced greatly. Therefore it is recommended for Royal IHC, to enter the conversation with Beele Engineering about turning into the new direction, and for Beele Engineering to work hard on the cost aspect.

ABBREVIATIONS

TSHD	Trailing Suction Hopper Dredger
COM	"Center Of Mass" used for algorithm
CSD	Cutter Suction Dredger
MST	Minimum Spanning Tree
PLV	Pipe Laying Vessel

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