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DESIGN FOR RETROFITTING

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Abstract

This paper explorers the possibilities to design a ship for a future 'sea change' like a major retrofit of the engine room. In order to assess the potential future beneficial impact of such design measures, a demonstrator method has been developed that scores a concept design for its 'Retrofit-penalty', thus allowing for comparison of design alternatives and what-if analyses in a very early stage. The conclusion is that such an approach is feasible, but in order to get more meaningful results further research on scaling of parameters is required.

Keywords: Design for X (DfX), Product lifecycle management (PLM), Product modelling, models

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1 INTRODUCTION

The intention of this paper is to demonstrate the more fundamental need of assessing the full operational life-cycle of a ship during the design stage. As a first exploration of this principle a relevant and actual example is taken: Current developments with respect to emission control put many ship owners in the position that they have to decide about a 'Retrofit'. A Retrofit is a refit of the ship's machinery or equipment with the specific aim to make the ship complying with more stringent environmental constraints. Because of the huge uncertainty of developments over the lifecycle of a ship, the future benefits of a Retrofit are difficult to assess. When an owner has to decide during the new-building phase about future provisions for retrofit, this is even a bigger dilemma. Therefore there is a need for a design method that systematically assesses the potential penalties and benefits of 'Design-for-Retrofit' (which will henceforth be abbreviated as 'DFR') A proposal for such a method is presented in this paper.

2 DESIGN METHODOLOGY

Design for X (DfX) is a generic name for the members of a family of methodologies adopted to improve design product as well as design process from a particular perspective which is represented by X." (Huang & Huang, 2002). Or: "The design for purpose, or DfX, intends to focus on the decision making process through the identification of the goal of the design." (Tomiyama, 2009). The 'X' can refer to a specific property e.g., cost, quality, lead time, efficiency, accessibility, flexibility or to a life-cycle phase of the product like manufacturing, assembly, service. After (Huang, 1996) the following requirements for a successful DFx method are suggested: It should: -Capture facts about products and processes; -Analyse relationships between products and processes; -Indicate performance, strengths and weaknesses, -Allow for 'what-if' analysis, analysis of proposed improvements and allow for iterations in design such that alternatives can be compared; -Provide redesign advice). It is acknowledged that "The research on design decision-making methods usually assumes that generating design alternatives is less an issue, rather the key problem of design is how to choose among given design alternatives." (Tomiyama, 2009).

This choosing among given alternatives can be troublesome: Although in the early stages of design of a ship a great degree of freedom exists with respect to choosing design alternatives this drastically reduces with every choice made by the designer and after the first design iterations costs of the total design are already committed to a large extent. 'Late' changes in the final product come at a dramatically higher cost due to the high degree of concurrent engineering and even time overlap between engineering and building of a ship (Coenen, 2014). So, in real-life the design solution space for ships and specifically Engine Rooms is small. Design Theory and Methodology recognizes a broad spectrum of design theories and methodologies and methods. In this paper a quick overview of these methods is given, not under the pretence of given a deep and complete overview but channelled to their applicability in shipbuilding and the presented example of Retrofit.

2.1 Design methodologies to enrich functional

In the next section relevant DFX methods are described:

Design-for-(dis)Assembly: this usually considers primary factors related to the subject product, including part symmetry, size, weight, fits, orientation etc. and the primary factors related to process as inserting, handling, gripping, orienting, special tooling etc. Often, reducing the number of parts for the product being designed and streamlining assembly operations and minimizing their cost can be a valid approach. It is assumed that streamlining for assembly is beneficial for disassembly as well as Mircheski states: "a proper design for disassembly is important to facilitate environmental protection and make the maintenance and repair of products more cost-effective" (Mircheski, et al., 2014). Wei Yan (Wei, 2012) shows in her research that assembly and disassembly sequence are in fact dual problems and that it can be assumed that assemble and disassemble sequences are in fact reversible. Huang (Huang & Huang, 2002) proposes the use of a so-called disassembly matrix that combines the interferences matrices in the directions of the x-, y- and z-axes. From this precedence relationships can be retrieved, that can analysed for instance by means of Petri nets (Moore, et al., 2001). A comparable problem is that of ‘Design for Reversed Logistics’. Often there is uncertainty in terms of the route and the time of technological operations, and the specific transport conditions that will apply. (Rohatynski & Sasiadek, 2014) is mainly interested in the transport of goods ‘after’ disassembly, but the question apply ‘during’ the disassembly (thus during the retrofit) as well. He proposes four criteria to determine the ‘difficulty’ of a disassembly operation. The ones relevant for Retrofit would be: -Accessibility; is there enough space? -Positioning; how precisely can a tool be set up to remove the element? -Force; amount of force required for disassembling and -Time required for disassembling; Mircheski proposes a method for optimizing the design for non-destructive disassembly of end-of-life products to optimise recycling. This method uses the (first version) 3D CAD model as input for an analysis of components and the way components are fastened together. From this an optimal disassembly sequence is generated and recommendations are made for redesign of product structure, fasteners and materials used.

The research of (Vliet, 2001) gives useful suggestions with respect to **Design-for-Manufacture** for quantification of x-ability. The following ingredients are suggested: Cost estimation, production time estimation, geometrical complexity, the number of process steps, number of processes, number of logistic actions, weight, dimensions, constraint satisfaction/violation, process properties. These are exactly the ingredients of a design parameter impact analysis as envisaged in the introduction of the paper. Looking ahead these number of processes, steps, logistic actions etc. should not only be considered for (new)building, but also for Maintenance, Repair and Overhaul (including Retrofits).

A more ‘generic’ DFX is **Design for Modularity**. A modular design is more resilient and adaptable to change (for instance of mission requirements). Modules are often used to share product characteristics between different product lines, generations or types; maintaining economy-of-scale advantages while offering a diversified gamut of products. Another reason for modularisation is an expected Technology push (the part is likely to go through a technology shift during its lifecycle because customer demands will change radically) or accommodation of variance in technical specification, for instance by parameterisation and choosing the exact spec as late as possible during manufacturing. Modular products also provide better possibility to upgrade and rebuild (and allow for quicker price estimations).MEKO is probably the best-known example of modularity in shipbuilding. In the patented MEKO concept, all components needed to run a specific system are accommodated in a single module and modules are connected to the power supply, HVAC, and the data network via standard interfaces. MEKO mainly focuses at sensor, weapons and communications systems. Another example is the 'Sigma' (Ship Integrated Geometrical Modularity Approach) philosophy of Schelde Naval Shipbuilding in which a set of geometrical parameters are defined which are applied throughout the entire product family, thus providing a repetition of identical units, both in the dimensioning of ship spaces as well as in the lay-out of systems. Furthermore, the hull form itself is 'modular'. With a few fore and aft ships, all hulls within the product family range can be created. The approach is applied at Schelde Naval Shipbuilding to a range of Offshore Patrol Vessels (OPVs). (Bertram, 2005).
From the viewpoint of the presented study (can modularity be seen as an optimization tool for the lifecycle of a ship?), the following question of Bradshaw is of interest: : 'How can modularity reduce maintenance? Modularity provides a reduction in maintenance because in a modular design optimized for maintenance, the components that have similar lifecycles are placed in the same module. Coordinating the replacement of these parts reduces maintenance time and equipment downtime. Furthermore, the need for interface standardization between modules permits new technology to be inserted more quickly. After all, part of maintaining a system is ensuring it does not become obsolete.” (Bradshaw, 2012). She consulted subject matter experts (SMEs), who answered a set of questions aimed at gathering the data necessary for the analysis. These questions related to the frequency or probability of change over the planning horizon due to a components own intrinsic technologies or contents (not because of other components around it changing) (and rationale); the expected typical cost of changing the component (both redesign cost and procurement cost; include just the cost for this component-if other components would necessarily have to be redesigned also, then that should show up as change propagations); the typical internal interfaces between components; the Probability of change propagation (and rationale), the estimated cost to reduce this probability (even possibility to zero) and finally how amenable is this interface to standardization? The first results of Bradshaw indicated that components with comparable interfaces could be modularised in order to reduce the

likelihood of change propagation across their interfaces. But the order of magnitudes of costs of components within a module should be more or less the same, in order to prevent modules being very much (order of magnitude) more expensive than replacement of their constituent components.
Modularity is related to scalable (namely parametric) product family design, whereby scaling variables are used to “stretch” or “shrink” the product platform in one or more dimensions to satisfy a variety of customer needs (Simpson, et al., 2001). Another approach is referred to as ‘configurational’ product family design, which aims to develop a modular product platform, from which product family members are derived by adding, substituting, and/or removing one or more functional modules. Interesting is the analysis of Nieuwenhuis (Nieuwenhuis, 2013), who introduces the concept of ‘overdesign’. Overdesign is the difference between the maximum performance of a design solution and the required performance. Examples of performance are installed capacity, installed quality, installed number of components. For the purpose of Design for Retrofit, ‘installed space’ could be added to this list. When taking a closer look into overdesign by means of ‘installed space’, the evaluation by (Keulen, 2007) is interesting as well. He shows that lowering the filling grade of a compartment in itself has a positive effect on engineering and production costs, but a negative effect on piping lengths. But making compartments smaller will only positively impact piping costs until a certain threshold value, because then because of blockages (other equipment standing in the way) the piping will have to increase in length.

2.2 DTM for new solution: Modification-based design

Modification-based design applies logical rules to existing designs and by systematically adding/exchanging/merging or removing of objects it is attempted to find a better solution. This could be:

Parametric design: a method in which the designer alters the parameters to explore various alternative solutions for a particular problem. The model will respond to modifications through automatically updating itself without deleting or modelling any elements. Looking for examples in ship design we see several interesting directions. A first approach is the so-called ‘packing problem’ which is a special class of space allocation problem. It is described in van Oers’ work (Oers, 2011). Geometric packing problems deal with placing several geometric objects such that: -All objects overlap completely with a larger positioning space; -All objects prevent unwanted overlap among themselves. Van Oers uses a search algorithm to generate a large and diverse set of ship designs that reflect a wide range of different compromises. Subsequently, the naval architect considers all feasible designs to gain insight in conflicting characteristics before selecting the most promising ship designs in a transparent manner. As van Oers states: “It proved able to establish the design impact of variations in payload and performance requirements. Moreover, the resulting set of designs was subsequently used to illustrate how the naval architect can identify and select designs that excel at particular performances, such as sea-keeping.” In this work also the useful distinction between non-negotiable vs. negotiable requirements is made.

The Theory of Inventive Problem Solving (TRIZ) is a series of tools and a methodology for generating inventive solutions for problem solving. For problem solving in TRIZ a specific problem is mapped to a more general contradiction specification, solved through the TRIZ toolset and mapped back to the specific situation. (McKesson, 2013) gives overview of how TRIZ can be applied in innovative ship design, but no specific examples. Key concept in TRIZ is to first state a design problem as a ‘contradiction’. For instance for the Retrofit setting: ‘How to design a room that leaves space for additional components without becoming larger?’, ‘How to design a room that leaves as much room for accessibility as possible, without becoming larger?’, How do we allow for ease of maintenance and repair, without taking up more space? TRIZ uses a fixed set of problem statements that are based on these contradictions. In this case for instance “Ease of Repair/Volume of Stationary Object” would apply, or “Volume of Stationary Object-Productivity” (Rantaren & Domb, 2002).
For these contradictions, the following principles could be suggested: **-Principle of ‘Taking out’**: Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object; **-Principle of ‘Partial or excessive actions’**: by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve; **-Principle “Preliminary**

action”: perform, before it is needed, the required change of an object (either fully or partially), like preliminary provisions of additional space and access paths, plug-and-play solutions etc.; **-Principle “Dynamics”** like dividing an object into parts capable of movement relative to each other; **-Principle “Segmentation”:** divide an object into independent parts, Make an object easy to disassemble or Increase the degree of fragmentation or segmentation.

Combining the above, the authors suggest a following grouping of relevant ‘Design Principles’ useful for ‘Design-for-Retrofit’. This list presented in Figure 1 is not exhaustive but intended as a ‘start set’ for systematically generating design improvements and alternatives. The results of applying these Design Principles can then be assessed based on their lifecycle and in this case specifically Retrofit merits.

1.Combination:
DFR 1.1 Modularisation: by grouping sub-functions. Modules drivers can be : carry-over (re use subsystem of an earlier generation); expected technology push, expected new release
DFR 1.2 Suggestions for simplification of product structure (DFX)
DFR 1.3 Integral construction: combination of several parts
2 Process/preliminary action
DFR 2.1 Application of non-destructive assembly whenever possible (bolts instead of welds etc)
DFR 2.2 Pre-provision tackling/transporting means
DFR 2.3 Pre-provision tackling/transporting routes (including hatches/doors)
3. ‘Splitting’
DFR 3.1 Differential construction: breakdown in easily dis-assembled parts
DFR 3.2 Reduce interdependencies by reorganisation of sub-functions
DFR 3.3 Move-out components of engine room
4. ‘Over’/excessive
DFR 4.1 Suggestions for better accessibility
DFR 4.2 Stretch/shrink to provide future user’s need
DFR 4.3 ’Overdesign”: over-capacity, over-quality, over-spaced.
5. Mixed:
DFR 5.1 Remove set of components (back to modularity) and repair elsewhere and then place back
DFR 5.2 Pre-install components or parts of components for future retrofit and install them later plug-and-play
DFR 5.3 Make parts movable or adaptable or extendible

Figure 1. Wrap up of Design Principles for Retrofit

3 DESIGN-FOR-RETROFIT-METHOD AND DEMONSTRATOR

3.1 Input for the Design-for-Retrofit Demonstrator

This section will demonstrate the effect of applying DFR principles and elaborates the ‘Retrofit Penalty Indicator’ concept. As explained in the introduction, DFR has the highest probability of success in the concept or basic design phase of a ship, when the design degrees of freedom are still high. Retrofit is not necessarily constrained to the design of a ship’s engine room, other parts like for instance the funnel (when installing a scrubber installation) or deck areas (when installing solar panels) can be involved as well. For purposes of demonstration, this paper will aim at the Engine Room.

The **Schematic Engine Room Layout** is a preliminary layout of the Engine Room that contains the ‘significant’ components represented by their boxed dimensions. The Schematic ER Layout represents the level of information a designer would have in the concept design phase**. Retrofit Actions** (the steps and work involved in execution of a Retrofit) are heavily related to the chosen **Access and Transport Routes**. The **Access Points** determine where a component can be taken out of the ship or brought in. Making use of existing hatches and doors versus creation of temporary access holes in bulkheads or decks or hull heavily impacts the course of Retrofit Actions. The **Transport Paths** are the routes that components (that are subject of Retrofit) take from their mounted position to the Access

Point or vice versa. If another object in the Engine Room blocks such a Transport Path, it needs to be dismounted and reinstalled as well.

A figure of an example ship's **Schematic Engine Room Layout** is given in Figure 2. In this figure a deck levels of an Engine Room is shown, with the main components positioned. The left part of this figure shows the Access Holes required for the removal of two auxiliary generators. For this specific situation it is assumed that no vertical transport takes places; the components will have to leave the room either through a cut hole in the side of the ship, or in case of the port side generator, that could be removed through the cargo ramp as well. Another example shown (on Steerboard) is a boiler, that only can be removed through the hull as well. Then the right part of the picture shows for these auxiliary generators the required Transport Paths that need be cleared to facilitate such a horizontal moving of the components.

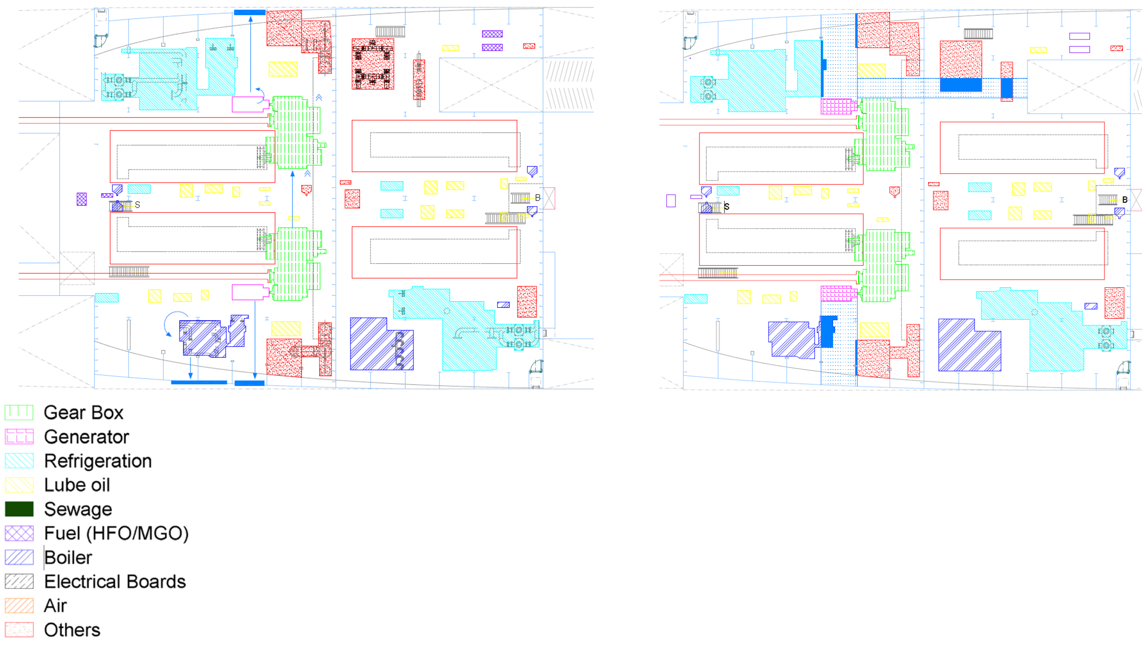

Figure 2. Schematic Engine Room Layout deck 1 and determination of transport path

3.2 Retrofit Penalty Indicator

The Retrofit Penalty Indicator is hereby introduced as a metric that expresses the (un)suitability of a ship layout for future Retrofits and can therefore be used to assess such a layout. The variables and parameters in the Retrofit Penalty Indicators have been based on subject matter aspect input.
The Retrofit Penalty Indicator is consists of a **Total Transport Penalty** and a **Create Access Penalty**. First the Transport Penalty will be explained.

Total Transport Penalty=

Ease of Handling*Filling Grade*(Length Horizontal Trajectory*Horizontal Transport Penalty*Horizontal Crossage Penalty + Length Vertical Trajectory*Vertical Transport Penalty

*Vertical Crossage Penalty) (1)

The **Ease of Handling** metric is –provisionally- based on the **box dimensions** and the exponent of the mass of a component.

Handle-ability=a*box dimensions*mass^0.5 (2)

Based on the Engine Room Volume and the box dimensions of these components, an indication of **Filling Grade** can be determined.

Filling Grade=sum of box volumes of ER components/Total ER volume (3)

This is only indicative as by far not all ‘volumes’ that take up space in an Engine Room can be taken into account by means of layouts as shown in Figure 2. This indication of filling grade can be used to relatively compare filling grades as the ‘real’ Filling Grade is considered to be proportionally related to the indication of filling grade in a provisional layout.

The **Horizontal/Vertical Transport Penalties** indicate if additional transportation means are to be provided for (Have hoisting beams already been installed in new-building, or are new tackles to be provided and certified? Can the component be hoisted out by crane, or does it need be put on rails first?)

Length Horizontal/Vertical Trajectories represent the transport routes of equipment (moving in- or out). This length is a function of the position of the component (p_c), the position of the **access point** (p_a) and the ‘best’ route from component to access point ($p_c \Rightarrow p_a$)**.**

The distances are measured by tracking the route to the nearest feasible ‘exit’. Such an exit can be an existing door/manhole/hatch, or an access hole to be created specifically for the purpose of disassembly. So in fact, when evaluating the Retrofit impact, assumptions about the disassembly approach have to be made. This aspect of routing is hugely simplified in this ‘Design-for-Retrofit’ demonstrator, as it is based on the schematic ‘box’ layout of the Engine Room. Different choices for routes can be feasible.

Finally a **Vertical/Horizontal Crossage Penalty** applies that accounts for passing through ‘difficult’ elements of the room, like tanks. The **no of boundaries to cross** like leaving a room or compartment is expected to put a time penalty on the disassembly action, because it requires coordination, more advanced positioning etc.

For the calculation of the transportation-related penalties unfortunately no reference figures are available, so these have to be chosen and scaled quite arbitrarily. Formula 2 also contains a scaling factor *a*. This scaling factor for **Ease of Handling** is –for purposes of demonstration- set to a=0.01, resulting in a unit of (kg^0.5)*m3/100. This implies that the value of the Total Transport Penalty in itself is not that meaningful, it can only be used for comparison between baseline and ‘post-redesign’ figures, but even then the quality of the results is much depending on the quality of the applied scaling between factors.

Then the **Create Access Penalty** is modelled as follows:

Create Access Penalty=

Area Horizontal Access Openings*(Unit Cost_{hor}+DCA_{hor}) +Area Vertical Access Openings

*(Unit Cost_{ver}+DCA_{ver}) (4)

If **Access Openings** are to be created, the effort involved can be based on rates that give hours/ton steel to be replaced (Butler, 2012). The mass of steel to be replaces is of course proportional to the dimensions of the opening and thickness of the plate. If such an access hole (in horizontal or vertical plane) also requires refit of ducting and cabling, this access hole penalty should be multiplied with a complexity factor, the so-called **Ducts/Cables/Armatures** factor (DCA). For this DCA factor it is assumed that there is a direct relation with the dimensions of the access hole and that the removal of Ducts/Cables/Armatures requires significant effort, with a same order of magnitude as that of the steel removal for the access hole itself.

Please note that the Total Transport Penalty cannot be meaningfully added to the Create Access Penalty if nothing is known about their mutual scale. As an example the calculated values for the casel layout of Figure 2 are shown in Table 1.

Table 1. Example Values for Main Engine

		floor dimensions component	side dimensions component	box dimensions	mass component	total 'handlebility'	deck	surface percentage (total ER)
		[m2]	[m2]	[m3]	[kg]	[m^3*kg^0.5/100]	[-]	[-]
0.1.1	**Main Engine 1**	**41**	**16**	**164.0**	**37000**	**315**	**1,2**	**5%**
0.1.1	**Main Engine 2**	**41**	**16**	**164.0**	**37000**	**315**	**1,2**	**5%**
0.1.1	**Main Engine 3**	**41**	**16**	**164.0**	**37000**	**315**	**1,2**	**5%**
0.1.1	**Main Engine 4**	**41**	**16**	**164.0**	**37000**	**315**	**1,2**	**5%**

		Length horizontal trajectory	Ease of Transport 'penalty'	Crossage' penalty	Length vertical trajectory	Ease of 'Transport 'penalty'	'Crossage' penalty	Overall Transport Penalty	Horizontal access openings 2b created	Vertical access openings 2b created	unit cost access opening	ducts/cables/armatures factor unit cost	Create Access Penalty
0.1.1	**Main Engine 1**	0	0	0	11.5	3	1	10883	0	48	300	180	23040
0.1.1	**Main Engine 2**	4.9	3	1	11.5	3	1	15521	0	48	300	180	23040
0.1.1	**Main Engine 3**	0	0	0	11.5	3	1	10883	0	48	300	180	23040
0.1.1	**Main Engine 4**	4.9	3	1	11.5	3	1	15521	0	48	300	180	23040

3.3 Assessing DFR Benefits

As a first exploration of the benefits of DFR this paragraph shows how the Retrofit Penalty Indicator decreases after redesigning the Engine Room based on the DFR principles of Figure 1. DFR methods from category 2 -'Process/preliminary action'- are chosen as being most illustrative to this case. An application of category 2 methods is changing the ER layout such that components with high transportation penalties are moved closer to their 'access/exit' point for disassembly. This can be considered to be a way of 'Modularisation' as well, as it requires grouping of 'minor components' to allow for such access routes. For each component that requires an Access Hole to be created, the most logical position and trajectory to this hole should be determined and then the rest of the box components should be moved out of these trajectories to cause the minimum interference. In addition, other model parameters would be affected (without changing the layout of the ER) as the surcharges on refit of piping/cabling could be reduced if it is managed to maintain 'obstacle free' area for future disassemble, or even the cutting of access holes could be prevented if hatches or other opening are foreseen (this would be reflected in the detailed ER layout of course, but not immediately in our box model). Also transport penalties could be avoided or mitigated by this DFR tactic. So, to demonstrate the Redesign on DFR Principles, two variants of the 'preliminary actions' principles will be checked:

a) Assume anticipated access holes free of cables/piping;

b) Moving components out of an anticipated 'component to Access Hole trajectory'.

This last option is in fact shown in the second part of Figure 2.

It is assumed that the Ease of Transport Penalty will drop to '2' because of the creation of a more obstacle free trajectory. The Penalty Indicator indicates that this might lead to a significant decrease of the Transport effort (~14%). The overall benefit would be lower as the creation of Access Holes does not benefit from this measure. Application of the DFR principle that results in a reduction of the Ducts/Cables/Armatures Factor might in its most extreme realisation lead to a 38% decrease in the 'Create Access Penalty. A combination of both principles would result in an even higher increase but for now the gains cannot be compared quantitatively. So beneficial impact is definitely expected from application of Design For Retrofit, albeit hard to quantify in this stage of the study. The used design performance factors are constituted of indicators of which the scaling has been performed arbitrarily, based on expert input, but without systematic validation. This needs more systematic research on the actual ship refit and repair processes and cost drivers. Qualitatively though, it can be concluded that the following DFR Principles show effect and could therefore be transferred into a design guideline:

Principle Pre-Provision of transporting Routes: If a Retrofit that requires the creation of an Access Hole is foreseen, it pays off to free this anticipated access hole as much as possible of minor components and outfitting. This in order of complexity, so first try to refrain from routing High Voltage cables or Hydraulic Pipes trough such an access route, then try to refrain from routing/positioning less complex items etc. This is not only relevant for anticipated Retrofits, but also for all other large components that have a high probability of 'needs-to-be-replaced' over the lifetime. It is suggested that ship owners put more effort in gathering such data and use them as input for the basic design of the Engine Room.

4 CONCLUSIONS

The demonstrator tool learns us that it is possible to estimate the impact of DFR principles applied on Ship Layouts, under Retrofit Scenarios. It also allows for demonstrating this in simplified CAD drawings, as usually applied in the early ship design concept stages, although in a rudimentary way. The demonstrator tools captures facts about products and processes, it analyses the relationships between products and processes, it indicate performances, strengths and weaknesses of DFR principles and scenarios, in such a way that alternatives can be compared. Indirectly, the tool provides redesign advice and allows for 'what-if' analysis and a first rough analysis of proposed improvements in design. It might therefore be helpful for execution an additional iteration –already in the very early concept design phase- to improve a design with respect to Design for MRO and Design for Retrofit. The main role of such a tool is creating awareness and not the numerical assessment as such.

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