Optimizing Spare Parts Inventory in Shipping Industry

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***Abstract*—The paper aims at proposing a criterion to optimize the initial level of spare parts inventory for a ship. Adequate stockholding of critical spare parts becomes essential in naval industry characterized by heavy utilization of equipment and machinery and by really specific operating conditions. Generic approaches are inadequate and specific ones result in analysis too shallow. An application for estimating the initial level of spare parts for a tanker is presented.**

Keywords-Inventory, spare parts, shared items, shipping industry.

I. Introduction

Inventories represent about one third of all assets in a typical company [1]. Really specific inventories are spare parts that require different policies from those, which govern WIP and final product inventories [2]. Importance of spare parts increases for industries characterized by heavily utilized and relatively expensive equipment [3]. The shipping industry is certainly in this category with a closer level of utilization and really expensive equipment. Moreover ships work in a very unique operational context, that makes the requirements of reliability and safety particularly critical. That is the reason for developing specific models to optimize the spare parts inventory in the shipping industry. Literature does not abound with models dealing exactly with this issue.

First contribution dates back to 1979 [4] and proposes a trade-off analysis between the inventory level and the ship reliability. From then on papers are substantially about two main issues. A part of them emphasises the forecasting models for predicting the demand for spare parts [5, 6] and they leave completely open the issue of the inventory optimization. Other papers study the ship spare parts inventory in base of different maintenance models. They aim at minimizing inventory cost [7] but their focus is on the maintenance policies rather than spare parts. Most exaustive approaches are from Cohen *et alii* [8, 9] but their works are quite dated.

Efforts for other industries such as manufacturing are really extensive but too general. We have gone through some relevant literature reviews [10-12] in order to catch the most significant contributions as basis for our studies. From this analysis the matter of this paper has taken shape. Our purpose is to propose an original approach to calculate the optimum level of inventory for spare parts of ship equipment. The basic assumption concerns the choice to consider the initial spares kit in order to move the focus from the maintenance policies to the inventory [13, 14].

Then we have decided to specialise the model dealing with the problem of shared items. We suppose to use ESWBS (Extended Ship Work Breakdown Structure) or some similar tool to breakdown the ship into three different levels: *(i)* System, *(ii)* Subsystem and *(iii)* Item. We define a part as shared if it can replace an item that works in different systems and/or in different subsystems (e.g., a bearing or a pump). Literature presents several general studies about the matter [15, 16, 17, 18] and many authors have debated about the economic advantage from the lower inventory and the risk pooling compared to the increase of purchase cost [19, 20, 21, 22], without coming to a final analytic model as we propose.

The paper is structured as follows: section 2 introduces the assessment of spare parts criticality as the basis for the model. Section 3 is devoted to deploy objectives and constraints to the problem. In Section 4 the procedure to optimize the inventory level is presented. The validation of the model through a case study for a tanker is included in section 5. Finally, section 6 summarizes the paper and provides some final remarks.

II. Spare Parts Criticality Analysis

A very common approach in dealing with the problem of inventory is to classify spare parts on the basis of level of criticality [23, 24]. Our proposal is to use a criticality threshold T in order to rank subsystems: only a subsystem with level of criticality exceeding T should be managed through the proposed model. Other subsystems with a lower level of criticality do not need specific approach. The criticality value could be calculated through different models into different context, but our advice is that criticality should be linked to the impact of the system malfunctioning on:

- Efficiency of the system in which the subsystem works, E_i^k;
- Efficiency of the whole ship, W_i;
- Safety, S_i.

For each subsystem *i* in the system *k*, the criticality value is:

$$s_i^k = E_i^k \cdot W_i \cdot S_i \tag{1}$$

with k = 1,…, K and i = 1, …, N_k.

Comparing s_i^k with T we have:

if $s_i^k > T$, then the subsystem *i* is in the optimization model;

otherwise, it is not.

For each item *j* working in a subsystem *i* the criticality value is:

$$k_j^i = s_i^k \cdot p_j^i \cdot \left(1 - A_j\right) \tag{2}$$

where:

p_j^i is the probability that the item *i* malfunctioning affects the efficiency of the subsystem *j*;

Aj is the item availability and

$$A_j = \frac{MTBF}{MTBF_j + MTTR_j + MTWS_j} \tag{3}$$

where

$MTBF_j$ is the Mean Between Failures;

$MTTR_j$ is the Mean Time To Repair;

$MTWS_j$ is the Mean Time Waiting Spare parts.

In reference to the parameters of this analysis, we have E, W and S that should be set through a quantitative and specific evaluation of the impact. In the section 5, in which we present a case study for a tanker, we also propose a structured matrix in order to calculate E, W and S for a pump. A and p can be estimated through a RAM analysis o some similar tool. Finally T is a really strategic parameter depending on the general trade-off between effectiveness and cost and on company policy. T could be also fine-tuned step-by-step.

A. Redundance function

The purpose is to build a specific function in order to describe the probability to spend the stock *x* of a part shared by n identical items j. The proposed function comes from the Reliability function for partially redundant systems [25] and it describes the Reliability at the time t of a system i in which n identical items j work and we have x spares to replace them.

$$R_i(x,t) = \begin{cases} \sum_{h=1}^{x+1} \binom{x+1}{h} \cdot R_j^h \cdot \left(1 - R_j\right)^{x+1-h} & se\ x \geq n_i^j \\ \sum_{h=n-x}^{n} \binom{n}{h} \cdot R_j^h \cdot \left(1 - R_j\right)^{n-h} & se\ x < n_i^j \end{cases} \tag{4}$$

where R_j is the reliability of the item j.

Please note that the function indeed underestimates reliability if $x \geq n$ because it takes into consideration even failures occurring among spare parts. In the case instead of $x < n$ the function actually describes the probability of not consuming the stock.

B. Availability function

The purpose is to build a function describing the time of unavailability of an item j in the subsystem i at the time of a malfunctioning.

$$B_i^j(x,t) = MTTR_j \cdot R_i(x,t) + (MTTR_j + MTWS_j) \cdot \left(1 - R_i(x,t)\right) \tag{5}$$

Through function in (5) availability can be calculated for subsystem i as in next section.

III. Objective function

One of the first issues of the problem is the choice of the objective – to reduce costs or to increase availability. We have translated them from objectives to contraints in order to take both into consideration.

A. Minimum availability

Spare parts are strictly linked to the availability of a system [26, 27]. We take into consideration the system k for which we have:

SL_k = the minimum required service level for the system k;

M_i = number of different items in the subsystem i;

N_k = number of different subsystems in the system k;

a^k_i = the probability for subsystem i to impact the availability of system k;

n^i_j = number of identical items of type j working into the subsystem i.

The unavailability of the system must be less than the minimum required service level as in the following:

$$\sum_{i=1}^{N_k} a_i^k \cdot \left(\sum_{j=1}^{M_i} \frac{n_j^i}{MTBF_j} \cdot p_j^i \cdot B_j^i(x,t) \right) \leq 1 - SL_k \tag{6}$$

(6) is true for each system k in the ship.

With reference to parameters p^i_j and a^k_i , it is possible to run a MAGEC analysis or FTA analysis in order to calculate them.

B. Maximum budget

The main idea is to balance two different cost figures: cost for ship unavailability and cost for holding spare parts in stock, i.e. capital, warehousing, depreciation, insurance, taxation, obsolescence, and shrinkage costs.

The cost for ship unavailability is formulated as:

$$C_{unav}(x,t) = \sum_{k=1}^{K} c_{unav}^k \cdot \sum_{i=1}^{N_k} a_i^k \cdot \left(\sum_{j=1}^{M_i} \frac{n_j^i}{MTBF_j} \cdot p_j^i \cdot B_j^i(x,t) \right) \tag{7}$$

where:

C^k_{unav} = cost for unavailability of system k;

K = number of systems in the ship.

And inventory cost is:

$$C_{inv}(x_j) = \sum_{j=1}^{n} c_{inv}^j \cdot x_j \tag{8}$$

where:

c^j_{inv} = cost for holding spare of item j;

Costs are considered both through the constraint in (9):

$$C_{unav} + C_{inv} \leq B_{\max} \tag{9}$$

Where B_{max} is the maximum budget.

IV. The optimization procedure

In order to optimize inventory on the basis of the above-mentioned parameters, we have developed a heuristic procedure:

STEP 0 : it represents the initialling of the procedure in which all variables x_j are equal to zero.

STEP 1: it calculates the following parameters for each item j:

$$W_j^i = k_j^i \cdot \left(\frac{R(x_j+1)}{R(x_j)} \right) \cdot \left(\frac{C_{unav}(x_j) - C_{unav}(x_j+1)}{c_{inv}^j} \right) \tag{10}$$

it represents the ratio cost/benefit if a x+1 part is in stock for the item j.

STEP 2: it selects the item j with the biggest value of W_j

STEP 3: it increases the inventory level of item j of a unit

STEP 4: it checks the respect of both constraints (5) and (8).

STEP 5: if the response from STEP 4 is NO, it goes to STEP 1; else STOP, the optimum inventory level has been obtained.

V. CASE STUDY

The proposed model has been tested to sort out the problem of optimum inventory level in a tanker, specifically a double-hulled vessel, which is used to transport refined petroleum products. It has a medium range and transport capacity between 45.000 – 51.000 DWT. Dead Weight Tonnage is a measure of how much weight a ship can safely carry. The model has been applied to the Inert Gas Generator. It works in order to create an atmosphere inside tankers in which the hydrocarbon oil vapors cannot burn. As a tanker is pumped out, it is filled with inert gas and kept in this safe state until the next cargo is loaded. The subsystems involved are the fuel oil pumps. Generally there are two pumps for each generator. An administration may permit only one fuel oil pump on condition that sufficient spare parts are carried on board to remedy any failure. The subsystem is critical because a malfunctioning could jeopardise the use of tanker or even could pollute the cargo. For the system has been also calculated the criticality level as in (1) using the parameters in Table I

TABLE I
Parameters for criticality level

E		W		S	
None	1	None	1	None	1
Use of stand-by part	2	Partial functioning at option level	5	PSC related	75
Partial functioning	3	Partial functioning at primary level	25	No manoeuvrability	500
Shutdown	4	Shutdown	125	Pollution	600
				Damage to person	750

Through “PSC (Port State Control) related” we intend that the malfunctioning must be reported to the port authority. According to (1)

$$s_{FUELOILPUMP} = 2 \cdot 25 \cdot 75 = 3750$$

That compared with a T = 750, it puts the system in the optimization model.

In Table II we report the items in the system and the number x_j of each item stored initially, before applying the procedure. Main data in Table II include the cost for holding spares of item j and the criticality level k_j.

TABLE II
Items in the subsystem

SYSTEM	**FUEL OIL PUMP**		
Item	$\mathbf{x_{START}}$	$\mathbf{c_j}$	$\mathbf{k_j}$
N°			
1	2	\$200	0,000103373
2	6	\$50	4,01974E-05
3	2	\$300	0,000179859
4	2	\$350	0,000149752
5	2	\$1.250	0,000146925
6	2	\$250	4,01974E-05
7	4	\$200	0,000182254
8	2	\$1.500	0,000109571
9	3	\$150	8,58677E-05

We have also considered a^k_i as 0,125 and a c^k_{unav} = \$ 400.000.

SL_k is fixed as 98% and maximum budget is \$ 20.000.

Before applying the procedure, the situation guaranteed the respect of main constraints, but the total holding cost was of \$ 9.250, the Service Level was of 98,02% and the Total annual Cost was of \$ 17.189,6.

In the Table III we report the number x of parts for each item after the optimization procedure that has gotten the optimum level at the nineteenth run.

TABLE III
Parts in the system after applying the procedure

SYSTEM	FUEL OIL PUMP
Item	X_{OPT}
N°	
1	4
2	1
3	3
4	0
5	1
6	0
7	5
8	0
9	5

In the Table IV we report the comparison between performance at the initial stage and after the optimization.

TABLE IV
Parts in the system after applying the procedure

Indicator	Initial stage	Optimization stage
Service Level	98,02%	98,02%
Holding cost	\$9.250	\$4.750
Total cost	\$ 17.189,6	\$12.678,32

So we can see that costs have greatly decreased despite a satisfied Service Level. In the Figures 1 e 2 we can see the trend of Service Level and Total cost iteration by iteration.

At the nineteenth iteration the procedure has found the inventory level as such as the cost is minimum and the Service Level constraint is satisfied. We have designed the curves even after the optimization in order to evaluate the general trend. After the optimization the Service Level grows step-by-step as well as the total cost until the maximul level defined by the budget constraint. In the following steps there is not another point of minimum cost and both service level bigger or equal than 98%.

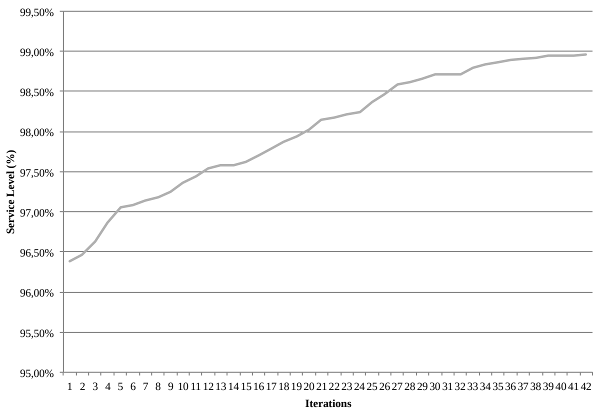

Figure 1. Service Level iteration by iteration.

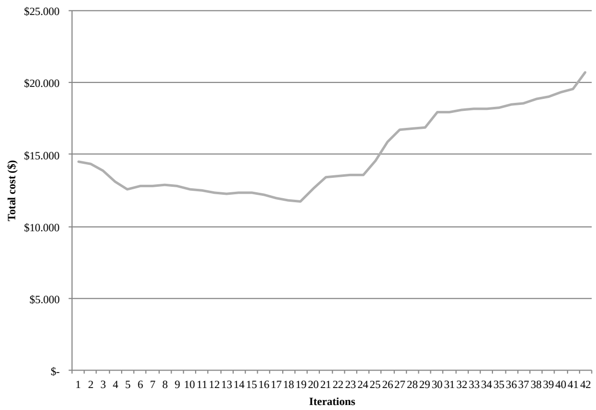

Figure 2. Total cost iteration by iteration.

VI. CONCLUSION

Through the proposed procedure the initial level of spare parts inventory for a ship is optimized. The procedure is specific for the problem and it is quite simple but effective. It meets the requirement of dealing with the problem of shared spare parts. The next step in the research should be an extensive application of the procedure to real cases in order to identify room for improvement from practical experiences.

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