On the relationship of spare parts inventory policies with Total Cost of Ownership of industrial assets

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Abstract: This work presents the results of a simulation study aimed at characterizing the relationship of spare parts inventory policies with Total Cost of Ownership of industrial plants. The study is motivated by the expectation that several spare parts management decisions cause important effects in the long-term profitability of industrial assets. Such decisions may regard, amongst the others, the initial provisioning, the inventory policy and the end-of-life acquisition. This work adopts simulation to test a specific spare parts inventory policy, i.e. a continuous review system, with the final purpose to assess its effects on the operational performance of an industrial comminution plant and, consequently, on its Total Cost of Ownership.

Keywords: Spare parts management, Inventory policy, Asset life cycle, Total Cost of Ownership.

1. INTRODUCTION

Total Cost of Ownership (TCO) is the sum of expenditures made by the owner of a physical asset along its entire life cycle. Those expenditures are required to acquire, install, put into service, operate, maintain and, eventually, dispose the physical asset. Those costs play an important role within the decision making process, especially regarding decisions on purchasing, maintenance planning, operations strategies, spare parts / logistics support design, as well as replacements and renovations.

Publications on TCO evaluation of industrial assets can be found in the scientific literature since 1970 (Kaufman, 1970; Ntuen, 1985; Taylor, 1981). From those years on, proposals of TCO models are present at a great extent. Nevertheless, despite it may seem an overcome problem, nowadays TCO is gaining momentum both in industry and scientific research (Thiede et al., 2012), and several gaps can still be identified when analyzing the state of the art. It is worth observing that, in the literature, the concept of TCO is strictly related to the concept of Life Cycle Cost (LCC), and a clear separation of these two approaches is often missing (Gram & Werner, 2012). Besides, it is evident that different views are proposed by different authors. Taking out few definitions from the scientific literature, TCO is considered a purchasing tool and philosophy aimed at understanding the true cost of buying a particular good or service from a particular supplier (Ellram, 1995), (Ellram & Siferd, 1998); TCO provides a selected perspective on LCC, focusing on the operator/user perspective of the considered object and all the costs that occur during the course of ownership (Thiede et al., 2012).

According to Roda and Garetti (2014), many existing TCO models lack in considering the performance characteristics of the industrial installations, i.e. physical assets, as a whole. Indeed, the operational performances achieved as a system (e.g. a production line, composition of machines) are rarely evaluated by means of a TCO model. In other words, besides availability, reliability, maintainability, other characteristics as the production capacity achievable by the system should be considered for a decision under a systemic perspective.

Maintainability is a key dimension for a physical asset, which leads to Key Performance Indicators (KPIs), such as MTTR (Mean Time To Repair). Through maintainability, a decision maker can be aware of the probability that failed equipment can be restored to its normal operable state within a given timeframe. One of the main aspects to guarantee or maintain a certain level of maintainability is spare parts availability. Therefore, a main concern when defining maintainability is the configuration of inventory policies (also stocking policies as synonym used by literature) for each spare part, in order to sustain the availability of the physical asset and, as a final consequence, to guarantee the capacity of the production system where the asset is operating.

Despite the importance of maintainability for physical assets, main effects of spare parts inventory policies are still poorly covered in economic evaluations along the asset life cycle, as demonstrated by the lack of models proposed that incorporate those aspects into TCO evaluation. Our interest is to reflect on this gap and, to this end, we decided to make a simulation study with the purpose to unveil the relationship between the spare parts inventory policies and TCO.

The paper is organized as follows. Section 2 provides a quick literature review focusing on the relationships between TCO /

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LCC models and spare parts management decisions. Section 3 provides a conceptualization of the relationship of spare parts inventory policies with TCO of industrial assets. Then, section 4 and 5 are dedicated to the simulation study: they are respectively presenting the simulation and cost models used for the study, and the analysis of the experimental results. Section 6 provides the concluding remarks of this work.

2. LITERATURE REVIEW ON TCO MODELS AND SPARE PARTS MANAGEMENT DECISIONS

Roda and Garetti (2015) proposed a Cost Breakdown Structure (CBS) for performing TCO analysis and trade-offs in order to suit the objectives of the company under concern.

Amongst the categories in the CBS there are the spare parts costs. In that category, many are the aspects that have to be considered, in terms of decisions. Briefly speaking, a series of spare parts management decisions can cause economic effects into TCO, as supplier selection, initial provisioning, stocking policy (i.e. inventory control and location), repair or replace policy, end of life acquisition, using/acquiring salvage spare parts, etc. …

If we also consider the environment where the physical asset is operated, a series of challenges and opportunities are influencing the spare parts management decisions and, thus, their economic effects measured by the TCO. Amongst them, it is worth considering the operational behaviour and characteristics of the asset (i.e. failures' dependencies, deterioration, changes in the process severity, etc. …), the management practices (i.e. standardization / commonalities of spare parts, outsourcing of inventory control to suppliers, decentralized stocks, co-operative stock pools, etc. ….), and the changes in the outer context (technology innovation, new commercial offers from spare parts vendors, etc. …).

Last but not least, spare parts classification is also worth of a remark, as a relevant step of the whole management process for driving decisions on spare parts (Roda et al., 2014). Many advantages can be achieved as a consequence of a proper classification, e.g. a company may align stocking policies with criticalities of the spare parts (Macchi et al., 2011). Therefore, it can be expected that a proper classification supporting criticality analysis will help a better control of the economic effects measured by the TCO.

Notwithstanding the importance of spare parts management decisions in practice, in an extensive literature review, few works have been found that address the integration of such decisions within TCO models. In Carpentieri et al. (2007) a simplified life cycle cost (LCC) model which integrates spare parts issues is proposed. In that work, the authors suggested the application of a simulation study to estimate the average monthly consumption rate of the mechanical and electronic components used by a production line. That work does not consider inventory policies or other aspects present in a spare parts management system. Carpentieri and Papariello (2006) incorporate operational aspects and spare parts management issues into a LCC model, taking into account the maintenance costs for two different maintenance policies (preventive and corrective) to calculate the costs of the spare parts that are annually required. Thus, a number of indicators is considered in their LCC model such as the total annual spare parts cost and the total maintenance hours required by a station, with logistics considerations about assembly and disassembly operations. Jun and Kim (2007) incorporated with more detail the spare parts aspect into a LCC model for a railway vehicle. They highlighted that an optimized strategy in spare parts management can decrease the operational costs. In their work they classified total LCC into two categories: recurring and non-recurring costs. Recurring cost (cost annually calculated) includes labour, consumable, power, on-going training, documenting and upgrading cost. On the other hand, the non-recurring cost includes initial spares, amongst others: they are calculated once when the asset is purchased, and they are usually added to the investment costs.

3. CONCEPTUAL MODEL ON THE RELATIONSHIP OF SPARE PARTS INVENTORY POLICIES WITH TCO

A conceptual model is now proposed to set the relationship of spare parts inventory policies with TCO (figure 1).

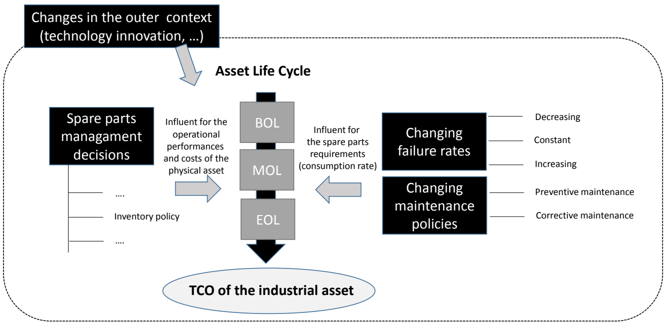

Figure 1. Conceptual model

Three inner dimensions (internal to the management system) are defined: i) spare parts management decisions, ii) changing failure rates and iii) changing maintenance policies along the life cycle. Besides, changes in the outer context are influent on such inner dimensions.

For what concern the first dimension, a lot of decisions can be identified in regard to the spare parts of physical assets. Spare parts inventory policy is one decision, amongst others. In particular, initial provisioning of spare parts is required at the Beginning of Life (BOL) of the physical assets. Besides, other decisions are needed, dealing with the inventory policy, repair or replace policy, locations (comparing centralized or decentralized stocking), etc... These may be changing along the asset life cycle as the environmental conditions change: decisions taken during the BOL may be modified, according to the new conditions experienced over the Middle of Life (MOL) of the asset. Eventually, there are decisions concerned not only with the End of Life (EOL) of the asset, but also with the EOL of the spare parts: obsolescence is a well-known problem occurring from time to time, requiring to identify the parts that have become obsolete, and to decide the new parts as substitutes. This is primarily due to the environmental changes in the outer context, e.g. technology, design changes, new commercial offers of spare parts vendor, whether or not the part is obsolete, which parts may be acquired, and the reviews of stocking policies, suppliers, etc. are then required at the EOL of the spare parts currently in use. All in all, this motivates that the concept of life cycle is a relevant dimension to organize decision making for the spare parts required by a physical asset.

Spare parts inventory policy is, as said, a decision, amongst others. To implement it and to define the stock sizes for the spare items, a company needs to select the inventory model amongst different options (Macchi et al. 2011), (Miranda et al. 2014). In this regard, it is worth remarking that literature is providing a wide set of models; the following list collects the majorly used or cited models:

- continuous review, that operates with fixed reorder point (s) and fixed order quantity (Q), referred to as (s, Q);
- periodic review, with fixed ordering interval (R), with fixed re-order point (s) and fixed order quantity (Q) referred to as (R,s,Q)
- periodic review, with fixed ordering interval (R) and order-up-to level (S), referred to as (R,S);
- continuous review, involving fixed reorder point (s) and order-up-to level (S), referred to as (s,S);
- periodic review, with fixed ordering interval (R), with re-order point (s) and order-up-to level (S), referred to as (R,s,S);
- continuous review and order-up-to level (S) in a one-for-one replenishment mode, referred to as (S-1,S).
- continuous review, with re-order point (s) one or zero policy that resolves the main spare parts problem: stock or no stock.

The inventory policy – in general, a spare parts management decision – should be assessed after taking into account the environmental conditions due to the assets: these lead to the second and third dimension of the conceptual model. Indeed, the consumption rate of the spare part is influenced firstly by the failure rate, as inherent characteristic, and secondly by the maintenance policies of the asset. On one hand, failure rate is traditionally seen through the theory of the bathtub curve. This has found in the Weibull distribution a popular model thanks to its flexibility in representing the different phases, featuring a decreasing, constant or increasing failure rate. More recently, studies are concentrating on the changes of the failure rates along the asset life cycle, leading to the proposal of new models in order to consider all the different phases along the time of the asset life cycle (e.g. Mahmoud and Mohammad (2010), Tian et al. (2014)). This enables to remark the need to consider that the reliability law / failure rate is not established once in the life; indeed, it is changing. Henceforth, from time to time, it leads to different conditions meaning, from the spare parts point of view, different usage patterns, which ultimately lead to needs to re-take decisions. On the other hand, once the reliability law / failure rate is given, different dynamics happen when preventive or corrective replacements (after the failure) are decided. As an example, preventive replacements can be originated by two different Preventive Maintenance (PM) policies, i.e. at constant ages or dates. Clearly, the choice of one of the aforementioned time based PM policies, combined with the randomness of the failure rate during the asset life, dictate a different order placement for the spare items, anticipating or delaying the correspondent cash flows. Figure 2a and 2b are exemplifying the different dynamics that can happen due to such policies. It is worth remarking that such dynamics are not fixed once in the life: as failure rates are changing along the asset life cycle, PM policies may change as well, thus leading to different dynamics.

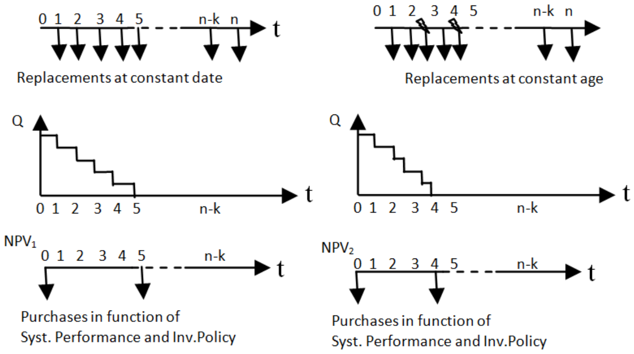

Fig.2. (a) Cash flow using PM (at constant date) and Continuous Review inventory model. (b) Cash flow using PM (at constant age) and Continuous Review inventory model.

All in all, changes in failure rates and in maintenance policies are relevant dimensions that are influent in the relationship of the spare parts inventory policy decision with the TCO of the industrial asset. More precisely, at the BOL of an asset, there is the need of evaluating different inventory policies and the effects that their operating parameters can cause into the TCO. That analysis may be re-taken (i.e. more than once) during the asset operation, i.e. the MOL phase, as the failure rates and maintenance policies could change. This may occur up to the EOL of the physical asset itself, or up to the EOL of the spare part when this happens before the EOL of the asset due to changes in the outer context.

4. THE MODELS ADOPTED IN THE CASE STUDY

The uncertainty along the asset life cycle is modelled through simulation: the stochastic functioning of the physical assets part of the comminution plant is represented by simulation to best fit the failure rates, thus the spare parts consumptions. According to the conceptual model presented in previous section 3, different timeframes may consider the changing reliability laws / failure rates along the asset life cycle. Nonetheless, due to the purpose of the study, the experiments shown in the remainder only consider a fixed probability distribution to generate data: a exponential distribution using a failure rate = 0,004 to generate the TBF (Time Between Failures) and a Weibull distribution to generate TTR (Time To Repair). The parameters of the probability density function were obtained after fitting real data. Generation is obtained by Monte Carlo simulation.

Besides, the Reliability Block Diagram (RBD) technique is used to represent the structure of the production system and the interdependencies among the various elements that make up the system. This enables to introduce the complexity of the system, as a set of physical assets combined according to their reliability logics (series, parallel and multistate system logics are considered for the case study). The logics allow analysing the performance of the system due to the physical assets for which spare parts inventory policies are planned. To provide a focused analysis in this study, generation of data is limited to a specific spare part required by a critical asset in the plant.

The model is implemented in R-MES (2015), a software for Reliability and Maintenance Engineering. R-MES enables a hierarchical modelling, leading to the possibility to represent different modelling levels, nested one within each other and usable for developing a simulation study at the needed extent of detail. The RBD of the plant is shown in figure 4, where the screen shot of the first level of the hierarchical model is depicted. The assets of the plant are crushers, feeders, transport belts, pumps, vibrating pan feeders, hydro-cyclones, ball mills.

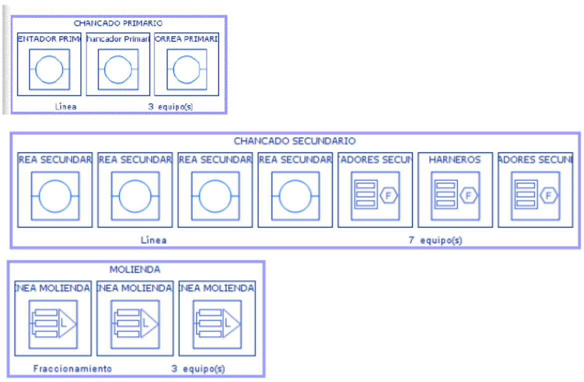

Fig.3. Reliability Block Diagram used in the simulation case

To understand the effects that different inventory policies, or decisions on certain inventory parameters, causes to TCO, we simulate three operating years. Such a timeframe is enough as the failure rate (so the consumption rate of the spare part) fits well the useful life of the asset under study.

Through that, we obtain the behaviour of the asset under study, considering the occurrence of both planned and unplanned maintenance (i.e. preventive and corrective maintenance). Assuming that each maintenance corresponds to a spare part replacement, it can be stated that the experiments consider both planned and unplanned replacements. The correspondent spare part consumptions, generated by the plant model, are used as input of a second model, that is the inventory model: the consumption rates are applied to a simulated stock operated according to a continuous review policy. Indeed, the experiments proposed in this paper consider the situation of a company that stores and manages a spare part according to the continuous review: the inventory level is continuously monitored and, as soon as it drops to the reorder point s, a new order, for Q units of the spare item, is placed with its supplier. Therefore, a series of experiments is performed using different stock parameters: Reorder Quantity (Q); Reorder Point (r); Initial Stock Level (S_0). Besides, whenever a stock-out happens, unavailability/down times of the physical asset are correspondingly calculated in the RBD model of the plant.

The economic assessment is carried out by computing the following cost components, used to form the cost model: the Holding Costs, the Acquisition Costs, the Stock-out Costs.

Holding Costs (HC_i) of a given spare part i is calculated by multiplying the average stock level in a given period (Qav_i) and a given value corresponding to the unit holding cost (Ch_i). The average level of a certain spare part in a given period strongly depends on the inventory policy and on the stock dynamics until the period under analysis.

$$HC_i = Qav_i * Ch_i$$

Acquisition Costs (AC_i) is obtained by the multiplication of the cost of placing one order of a given spare part (A_i) and the number of orders placed during a given period ($Nord_i$).

$$AC_i = A_i * Nord_i$$

The Stock-out Costs (SC_i) are calculated by the multiplication of a fixed value that represents the unitary stock-out cost (Sc_i) of the spare item and the average stock-out quantity of the corresponding period ($Sout_i$):

$$SC_i = Sc_i * Sout_i$$

The stock-out quantity is measured as the loss of production quantity, proportional to the unavailability/down times of the physical asset. Owing to the series logics of the assets where failures are generated, this corresponds to the loss at the plant level.

The Total Cost (TCi) is eventually calculated – in its holistic version – by the summation of the three aforementioned cost components:

$$TC_i^{hidden+logistic\ supports} = HC_i + AC_i + SC_i$$

Another cost function is adopted, limited to cost components related to the logistics support.

$$TC_i^{logistic\ supports} = HC_i + AC_i$$

The Total Costs of each one of the three years considered in the experiments are computed. Then, the three values are used to calculate the financial indicators, by means of the actualization of the cash flows, such as the Net Present Value (NPV).

5. THE EXPERIMENTAL RESULTS

Table I and II show the experimental results, reporting the NPV of the inventory policy (note that the discount rate for the NPV calculation is equal to 10 % per year) and the Availability of the asset.

The results are obtained based on a set of scenarios designed to compare the different inventory policy parameters, i.e. s and Q. Besides, the Initial Stock is the initial provisioning of spare parts assumed at the beginning of the operating time under concern for the policy decision.

Overall, the experimentation allows comparing the NPV, as a measure of the effect caused into the TCO of the asset, and the Availability as a well-known technical measure of the asset.

Table I. Availabilities obtained in each of the test cases.

Reorder	Reorder Level = 4				Reorder Level = 3				Reorder Level = 2				Reorder Level = 1			
Quantity	I.Stock:5	I.Stock:4	I.Stock:3	I.Stock:2	I.Stock:5	I.Stock:4	I.Stock:3	I.Stock:2	I.Stock:5	I.Stock:4	I.Stock:3	I.Stock:2	I.Stock:5	I.Stock:4	I.Stock:3	I.Stock:2
6	99,3%	99,3%	99,3%	99,3%	99,3%	99,3%	99,3%	98,7%	99,3%	98,0%	98,0%	96,7%	97,4%	94,8%	94,2%	94,8%
4	99,3%	99,3%	99,3%	99,3%	99,3%	99,3%	99,3%	98,7%	97,4%	98,7%	98,7%	96,1%	89,7%	91,0%	96,1%	92,9%
2	99,3%	99,3%	99,3%	99,3%	99,3%	98,7%	99,3%	98,7%	95,5%	95,5%	95,5%	95,5%	71,2%	66,7%	71,2%	66,7%
1	93,6%	93,6%	93,6%	93,6%	86,5%	86,5%	86,5%	86,5%	74,4%	74,4%	74,4%	74,4%				

Table II NPVs obtained in each of the test cases.

Reorder	Reorder Level = 4				Reorder Level = 3				Reorder Level = 2				Reorder Level = 1			
Quantity	I.Stock:5	I.Stock:4	I.Stock:3	I.Stock:2	I.Stock:5	I.Stock:4	I.Stock:3	I.Stock:2	I.Stock:5	I.Stock:4	I.Stock:3	I.Stock:2	I.Stock:5	I.Stock:4	I.Stock:3	I.Stock:2
6	$ 1.905,08	$ 1.833,07	$ 1.848,34	$ 1.920,80	$ 1.656,42	$ 1.646,45	$ 1.574,44	$ 1.606,24	$ 1.309,77	$ 1.432,50	$ 1.427,81	$ 1.381,92	$ 1.199,77	$ 1.177,08	$ 1.314,70	$ 1.293,48
4	$ 1.796,23	$ 1.751,69	$ 1.741,29	$ 1.848,61	$ 1.593,61	$ 1.537,60	$ 1.493,06	$ 1.493,18	$ 1.287,44	$ 1.353,16	$ 1.295,49	$ 1.317,07	$ 1.311,33	$ 1.264,01	$ 1.180,48	$ 1.205,62
2	$ 1.985,32	$ 2.033,61	$ 1.992,59	$ 2.037,25	$ 1.767,71	$ 1.743,22	$ 1.774,98	$ 1.750,49	$ 1.581,44	$ 1.609,90	$ 1.592,35	$ 1.617,18	$ 2.461,95	$ 2.691,39	$ 2.472,86	$ 2.702,30
1	$ 2.831,01	$ 2.841,92	$ 2.851,01	$ 2.858,29	$ 2.906,76	$ 2.919,49	$ 2.930,40	$ 2.939,49	$ 3.311,60	$ 3.326,15	$ 3.338,87	$ 3.349,78				

More specifically, the scenarios enable testing a range of approaches, from conservative strategies (in case of high value of fixed reorder point s and fixed order quantity Q) to risky strategies (in case of low value of the same parameters s and Q), inclusive of the intermediate situations (combining high and low value for s and Q). Such kind of tests enables some observations:

- minimum costs and maximum availabilities are achieved with different parameters of the inventory policy; indeed, the lowest costs are reached with the lowest values of reorder point, while the maximum availabilities are reached with the highest values of reorder points;
- costs increase when the order quantities decrease; therefore, the highest order quantities allow the lowest costs with a given reorder point;
- the highest order quantities also allow the highest availability, especially with the highest values of reorder points.

This outcome cannot be generalized as it depends on the unitary costs used in the case study (Ch_i=*$2;* A_i = $20; Sc_i= *$*20). Nonetheless, it allows reflecting on the drivers of the strategies that may be relevant for a decision maker.

Generally speaking, it is obvious to assert that the strategies are driven by the objective of the decision. The case study shows the driver, i.e. the existence of a tradeoff between costs and technical measures (NPV versus Availability), which may occur subsequent to the specific unitary costs. More specifically, it is evident that a decision featuring a partial risk (i.e. an intermediate strategy between the fully conservative and the risky strategy) may be acceptable: this could happen, as in the case study, when the unitary stock-out costs assumes values comparable to the other costs associated with the logistics support. Indeed, the experiments herein presented enable to state that, as strategy, it is better waiting to reorder at the lowest stock level as possible – leading to a partial risk of stock-out, but saving the number of times that the order is placed. On the other hand, big quantities should be ordered enabling, at the cost of inventory holding, to limit the risk not to achieve the targets, i.e. low NPV and high Availability.

Overall, the experimental results put in evidence that the decision is influenced by the Cost Breakdown Structure. The cost function provides a holistic model of the incurred costs. This means that the decision should be based not only on the costs associated with the logistics support, but also on the hidden costs correspondent to the unavailability of the spare parts in the inventories (i.e. stock-out costs). This leads to a decision that considers the subsequent effects on operational performances, such as the plant downtimes while it is also aligned with the aim of TCO evaluation and improvement. Depending on the unitary costs characterizing the Cost Breakdown Structure, the decision-making strategies may change. If, for example, we were experimenting with a much higher stock-out unit cost, we could expect a change orienteering to a more conservative strategy – i.e. high reorder level associated with high order quantities – in order to keep high Availability.

6. CONCLUSIONS

TCO is a useful concept for asset managers to support their decision making process. During the entire life cycle of any physical asset, managers face crucial questions in regard to purchasing, maintenance, replacements, spare parts / logistics support design, etc.

The present work raised attention on the spare parts management decisions, for which there is a series of issues to be solved with respect to the BOL, MOL and EOL phases of the asset life cycle. All those issues may cause important effects into economics, thus, their incorporation has to be considered highly relevant for the implementation of TCO evaluation.

In a literature review it was understood that few works have effectively addressed the definition and implementation of TCO models for supporting decisions on assets integrated with spare parts concerns. Then, we defined and implemented

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a simulation based methodology for the analysis of several spare parts management decisions. The methodology was based on a conceptualization leading to foster future works as follow-up of this research, in regard to the study of different spare parts management decisions along the asset life cycle and their relationship to TCO.

Based on such a wide concept, the simulation study aimed at supporting the specific analysis of an inventory policy and its operational parameters. The modelling approach was divided into three stages. The first stage implemented a Monte Carlo simulation to generate planned and unplanned maintenance of each physical asset, and a RBD model of the production system, composition of the physical assets, to measure the effects at system level. The second stage, relating to the stock simulation, used the spare parts consumptions resulting from the planned and unplanned maintenance generated in the first stage. The third and last stage regarded the calculations of cost components, effects of the dynamics outcome of the first and second stage: the costs were structured as cash flows and the related financial indicators, as Net Present Value (NPV), were obtained. It is worth pointing out that the economic effects of maintainability were also including the stock-out costs, in order to consider longer downtimes and their effects on the availability of the physical assets in the system.

Future works aim at testing other inventory policies, while also measuring the effect of lead time variability and joint consumptions of spare parts. In addition, using the simulation based methodology, one can analyse other strategies such as an end of life acquisition, or adding disposal related costs if a given quantity remaining at the final period of the useful life. Such remaining stock can be considered as an additional revenue opportunity if that stock can be bought by any interested user elsewhere, or can be configured as additional disposal costs, if the company must pay for anyone to retire it.

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