Application of a Performance-driven Total Cost of Ownership (TCO) Evaluation Model for Physical Asset Management

Irene Roda and Marco Garetti

Abstract The core concept of this paper is total cost of ownership (TCO) of industrial asset and its relevance in supporting decision making if properly evaluated through the analysis of the technical performances of the asset. The paper is based on a framework that systematizes benefits and potential applications of TCO for different kind of stakeholders at different stages of the life cycle of the asset, supporting different kind of decisions. The aim is to present an experimental case study that has been implemented in order to show the empirical evidence of what is in the framework by focusing on one of the primary companies in the chemical industry in Italy. The application proposes a modeling approach for trying to overcome one main gap that still subsists when referring to TCO models that is that most of the existing ones lack of the integration of technical performances evaluations into the cost models or are based on very limiting hypothesis. In this paper a comprehensive methodology for the evaluation of Total Cost of Ownership of industrial assets that has being developed within a research activity carried out at the Department of Management, Economics and Industrial Engineering of Politecnico di Milano is presented.

Keywords Asset management performance · Total cost of ownership · Asset performance measurement

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1 Introduction

In order to meet the challenges of global competition and changing market conditions, production companies need to adopt an asset management strategy and system to sustain or improve the life cycle profits of the original investment [11, 12, 18]. With this regard, one of the challenges in the physical asset management field is to keep a life cycle perspective whenever a decision is taken both for acquisition or configuration and management actions on any asset. Through this perspective, it is essential to improve the quantification process of costs, in order to be able to evaluate the total cost of operating a production system throughout its life cycle (i.e., the so called Total Cost of Ownership (TCO)) as supporting evidence that allows informed decision-making [27].

More in detail, this work refers to the concept of TCO intended as the actual value of the sum of all significant costs involved for acquiring, owning and operating physical assets over their useful lives [37]. TCO is strictly related to the concept of Life Cycle Cost (LCC) and they are often used without distinction in literature. The widely shared idea is that TCO provides a selected perspective on LCC. In contrast to LCC, it focuses on the ownership perspective of the considered object and all the costs that occur during the course of ownership [19]. Moreover [8] and other authors later on, used it with a more strategic connotation, giving to TCO the meaning of a supporting information for strategic choices regarding both investment decisions and operational strategies.

It is widely accepted in the academic literature [32] that TCO should be an integral part of an asset management strategy and the same is assessed by the ISO 55000 series of standards for asset management. In particular, the latter puts into evidence the relevance of being able to quantify the TCO of an asset, being it an industrial system or a single equipment, and it is indicated that: "[…] Life cycle cost, which may include capital expenditure, financing and operational costs, should be considered in the decision-making process. […] When making asset management decisions, the organization should use a methodology that evaluates options of investing in new or existing assets, or operational alternatives" [13, Sect. 6.2.2.4]. On the industry side, companies are more and more acknowledging that a TCO model can represent a reliable economic-sound support for taking decisions and conveying the information it represents to both internal and external (costumers/suppliers) stakeholders [1].

This paper refers to the framework (Table 1) that the authors developed based on an extensive literature review aiming at highlighting the benefits of the adoption of a TCO model in decision making support for asset management [28]. Developing the framework, three main dimensions have been identified:

a. type of stakeholder: given the meaning itself of TCO, it is evident that asset users (asset owners/managers) are the main stakeholders; nevertheless asset providers (asset builders/manufacturers) have also interest in evaluating the TCO of assets they build/sell.

Table 1 Framework of benefits of TCO adoption in decision making for asset providers/users

	Asset provider		Asset user	
	Configuration	Management	Configuration	Management
BOL	Evaluation of project alternatives	Communicating value to the customer and selling support	Evaluation of design alternatives offered by a provider	Suppliers and tenders evaluation and selection
	Comparison and optimization of design alternatives	Propose to the clients specific design solutions		Maintenance service contract evaluation
	Components/equipment procurement and construction alternatives evaluation	Pricing		Investment, budget planning, cost control
	Spare parts requirements estimation	Contracting maintenance services provision		
MOL	Proposal of re-configuration solutions	Maintenance service provision offering	Reconfiguration decisions	Maintenance scheduling and management
		Spare parts provision offering	WIP sizing	Repair level analysis
				Asset utilization and production strategies
EOL	Proposal of reconfiguration for EoL optimization	Evaluation and proposal of rehabilitation strategies	Reuse strategies for components/machines	Evaluation of rehabilitation strategies

b. type of supported decision: a TCO model has got potentiality to support different kinds of decisions and in the framework two main categories have been identified:

   (i) configuration decisions and
   (ii) management decisions.

c. phase of the life cycle: TCO analysis can be carried out in any and all phases of an asset's life cycle (Beginning of Life (BOL), Middle of Life (MOL) and End of Life (EOL)) to provide input to decision makers.

The framework shows which benefits a TCO model can bring to each of the two types of stakeholder at each lifecycle phase by supporting different kinds of decisions (configuration or management decisions).

2 Problem Statement and Objective

Even if it clearly emerges from the literature that TCO has got positive effect in supporting decision making for asset management; however, many limitations exist up to day. The main issue is that most of the TCO methods developed so far only consider the cost but neglect the performance of the system, which has significant limitations [6]. A crucial point in order to understand the applicability of a TCO model for supporting physical asset management is that the evaluation criteria for the costs elements definition should encompass not only all incurring cost elements along the asset life cycle but also system performance characteristics, like system availability, in upfront decisions for achieving the lowest long term cost of ownership [8, 17, 37].

Indeed, some main issues should be considered when approaching the TCO evaluation of a production system as a support for decision making:

i. a large number of variables directly and indirectly affect the real cost items and are affected by uncertainty in their future evolution (e.g. inflation, rise/decrease of cost of energy, cost of raw material, cost of labor, budget limitations, etc.) [9, 26];
ii. the evolution of asset behavior in the future is difficult to predict (e.g. aging of assets, failures occurrence, performance decay) and 'infinitely reliable' components or systems do not exist [31];
iii. complex relationships in the assets intensive system dynamics, due to the presence of many coupled degrees of freedom, make it not easy to understand the effects of local causes on the global scale [38];
iv. conventional cost accounting fails to provide manufacturers with reliable cost information due to the inability of counting the so-called invisible and, in particular, intangible costs, and thus there is inaccuracy in calculating total costs [7].

It is evident that additional research is required to develop better TCO models to quantify the risks, costs, and benefits associated with physical assets including uncertainties and system state and performance evaluations to generate informed decisions [33]. The objective of this paper is to present a comprehensive methodology for the evaluation of the TCO of industrial assets that has being developed within a research activity carried out at the Department of Management, Economics and Industrial Engineering of Politecnico di Milano. The methodology is based on an integrated modelling approach putting together a technical model for the evaluation of the technical performances of the asset over its lifecycle (by accordingly generating the asset failure, repair and operation events) and a cost model for evaluating the final cost breakdown and the corresponding TCO calculation (Fig. 1). An industrial application case study has been implemented and first experimental findings of developed methodology are presented showing the relevance and potentialities of such approach for companies.

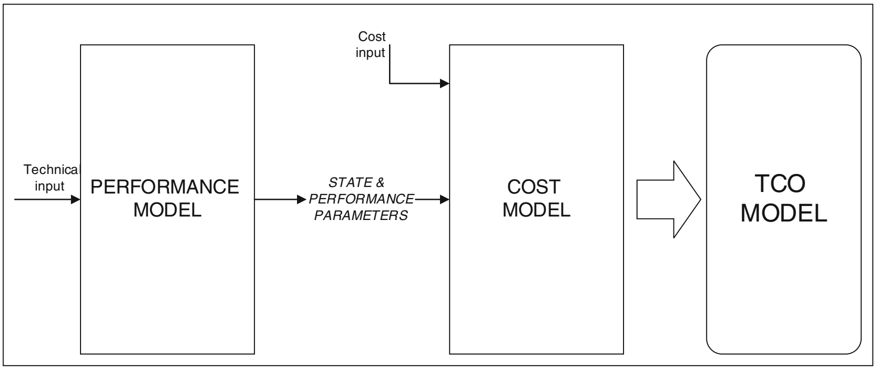

Fig. 1 Concept of integrated TCO evaluation model

3 Performance-Driven TCO Evaluation Methodology

The TCO methodology that is presented in this paper, is based on the idea that only by the integration of a performance model and a cost model is it possible to develop a reliable TCO model to support strategic decision-making (Fig. 1).

The underlying assumption is that proper system modeling has to be introduced for availability, maintainability and operation and that it must be integrated with a cost model for economic evaluations.

Cost model:
Whilst there is general agreement that all costs occurring along the life cycle of an asset should be included in the related TCO model, opinion varies as to their precise identification [37]. Several cost models have been proposed in literature and different ways to categorize the main cost items can be found. Some models group cost items depending on the life cycle phases of the asset, others refer to the two main categories CAPEX and OPEX. In spite of these different categorization approaches, in the end the detailed costs items list will depend upon the particular system under consideration and a cost break down structure (CBS) approach is commonly adopted [4, 17]. The important point is that the cost structure must be designed so that the analyst can perform the necessary TCO analysis and trade-offs to suit the objectives of the project and the company concerned [37]. Table 2 shows the CBS that has been defined for the specific case study that is presented in Sect. 4. The specific cost model includes the main cost items that are usually considered by a manufacturing company for evaluating different design solutions for production systems.

A relevant issue that must be taken into account and that is mostly undervalued in practice, is the need to include those cost elements that depend on the performance of the system within the cost model. For example, it has to be considered that when an asset fails, the cost is not limited to the cost of repair or replacement (in terms of manpower and material), but the money lost because the asset is out of service must be included as well [35]. The same is valid for other performance

Table 2 Cost categories in TCO cost model

Summary of costs per category	
CAPEX	OPEX
1. Purchasing price	7. Energy cost
2. Installation fixed cost	8. Line operators labor cost
3. Civil works cost	9. Maintenance visible cost
4. Commissioning cost	9.1. Maintenance personnel cost
5. Extra cost	9.2. Spare parts cost
6. Installation labor cost	10. Losses related costs
	10.1. *Management losses costs*
	10.2. *Corrective maintenance downtime losses costs*
	10.3. *Speed losses costs*
	10.4. *Non-quality costs*
	10.5. *Labor Savings*
	END OF LIFE COSTS AND SAVINGS
	11. Decommissioning costs

losses consequences (e.g., quality losses, speed losses etc.). All these aspects must be considered within a complete TCO model, hence it is necessary to evaluate and to quantify factors that allow predicting the form in which the production processes can lose their operational continuity due to events of accidental failures and to evaluate the impact in the costs that the failures cause in security, environment, operations and production [26, 36].

To this regard, a widely used performance measure in the manufacturing industry is overall equipment effectiveness (OEE) originally introduced by [25, 14]. It is clear that for making asset management decisions it is important to have a thorough insight into all involved costs and their impacts on the profit and competitiveness. Managers need to consider the trade-offs between the amount of investment and its impact on the OEE and TCO becomes an indicator required for competitiveness analysis [13]. The following Fig. 2 shows which are the losses that have been considered into the cost model in the methodology herein proposed, by referring to OEE. The identified losses (availability, performance and quality losses) lead to specific cost items in the OPEX category of the cost model (Table 2, cost items under category 10) and they must be evaluated through a performance model as it is detailed in next section.

Performance Model:
As assessed above, system state and performance evaluation is an essential step that needs to be developed to feed with the proper inputs the cost model, hence to evaluate the real TCO referring to an asset.

Obviously in complex systems, OEE should be calculated at system level, by correctly considering the result of dynamic interactions among various system components (i.e. individual assets). This issue has been identified by [15, 23, 24]; and the latters introduced the term overall throughput effectiveness (OTE) as a

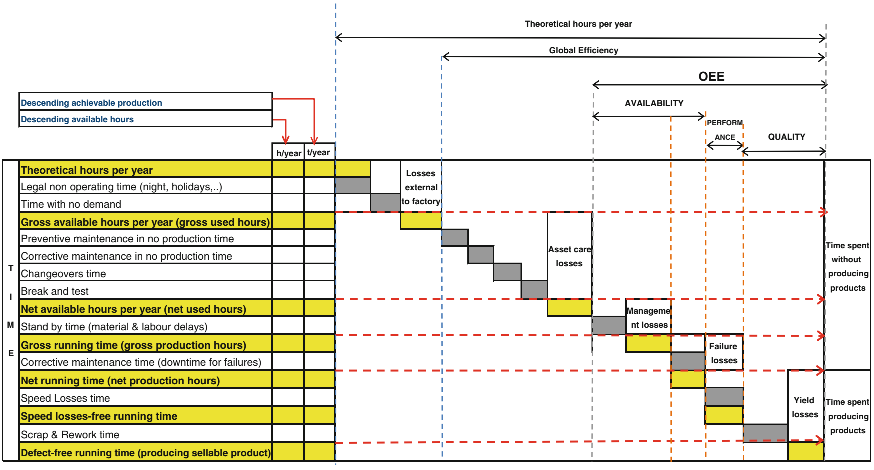

Fig. 2 Outline of losses and OEE calculation scheme

factory-level version of OEE that takes the dependability of equipment into account. Some approaches have been proposed in literature in order to try and face the quantification of costs related to system unavailability. On one hand, the most traditional approach is to use ex-post analysis as a calculation based on historical or actual data; applying the traditional RAM analysis based on statistical calculations or probabilistic fittings. On the other hand, great potentialities are added by applying ex-ante estimation aiming at a static or dynamic prediction of total costs through estimated behavior over the life cycle [34]. Within this second perspective, some works have been proposed in literature suggesting the use of stochastic point process [16, 19, 26] and some others propose the use of simulation based on the Monte Carlo technique [10, 30, 33]. In this work, the stochastic simulation is proposed for modeling the casual nature of stochastic phenomena and the Reliability Block Diagram (RBD) logic is used to express interdependencies among events thus evaluating how individual events impact over the whole system (Fig. 3).

The Monte-Carlo method is used for generating random events relying on the statistical distribution functions of the time before failure (TBF) and time to repair (TTR) variables given as input values at component level. Both failures modes and stops of the system related to other reasons (such as operations problems) can be considered. Using the simulation technique, the system behavior can be generated in a series of random iterations by calculating as a final result, a statistical estimate value of operational availability and OTE for the complete system. One of the main disadvantages of the use of simulation is the high effort that it requires for making the system model and data preparation [17]. To this regard, new approaches are introducing the use of some conventional modeling techniques such RBD for simulation purposes [20, 21, 29]. In fact the RBD logic has the advantages of giving a systemic, integrated and very compact view of the system with a bottom-up perspective while keeping an easy implementation approach. In order to ease

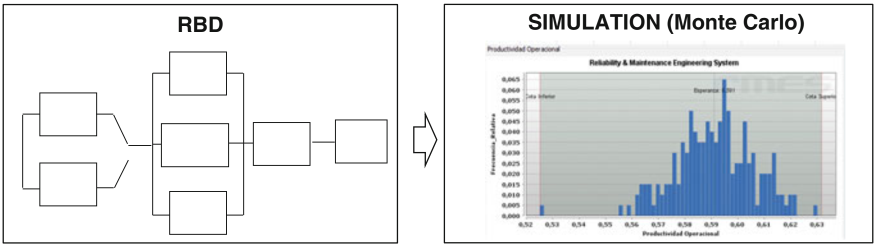

Fig. 3 Tools for the performance evaluation model

application, these concepts have been embodied recently in several software based tools for asset management which use simulation (such as for example Availability Workbench™ by ARMS reliability; Relex or R-MES Project©). Within this approach, aspects that go beyond the pure unavailability evaluation determined by asset failures can be considered such as production losses due to system performance or quality reduction.

This approach has been adopted in the proposed model for the evaluation of technical performances. The performance model allows evaluating the OTE of a system by taking into account assets behavior and dependability during equipment lifecycle. Such information is a relevant input for the evaluation of the OPEX cost components within the cost model (Table 2).

After the evaluation of the costs elements using the outputs of the simulation where needed, the sum of all costs can be actualized through the evaluation of the Net Present Value (NPV) or the Average Annual Cost of the TCO.

4 Application Case

4.1 Background

The performance-driven TCO calculation methodology has been applied in a case study regarding a primary chemical company in Italy, particularly concerning an industrial line for rubber production. Next Fig. 4 shows the basic process flow-sheet and the main equipment composing the plant section under analysis. The main objective of the case study is to apply the developed TCO evaluation methodology to prove its potentialities for supporting decision making.

Basing on the framework presented in Sect. 1, the methodology is applied by the *user's* perspective (owner and manager of the plant) dealing with the Middle of Life phase of its asset. The main potentialities expected from the evaluation of the TCO by the plant management are to support re-configuration choices through an economic quantification of the effect of technical changes in the plant. Hence the focus is on reconfiguration decisions/new acquisition investments.

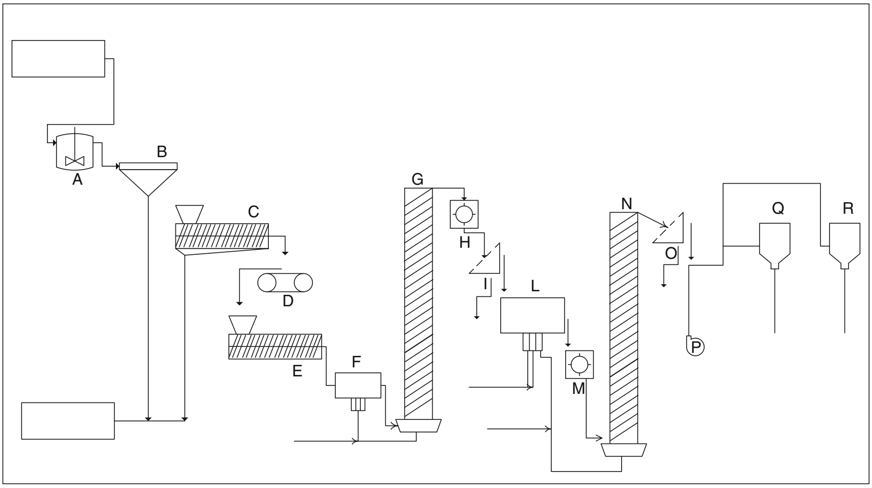

Fig. 4 The case-study production line

4.2 TCO Evaluation Procedure

The case is based on the use of the TCO evaluation methodology that has been presented above based on the cost model and performance model. In particular, the following steps have been developed for the application case.

Performance evaluation:

Step 1. Process understanding and system's components identification.
Step 2. Identification of failures modes or stop causes of each component.
Step 3. Reliability, maintanability and operation data acquisition (TBF and TTR).
Step 4. Modeling of the as-is system through RBD logic.
Step 5. Simulation (Monte Carlo).
Step 6. Technical performance calculation of the system.

On the basis of the given situation, 156 equipments have been put in the model and simulation runs (200 runs) were conducted in order to calculate the operational availability and OTE of the as-is situation over a time span of 5 years.[1] Such data was used as one of the inputs for the following cost modelling phase.

Cost evaluation:

Step 7. Cost model setting (Table 2).
Step 8–9. Cost data acquisition and Calculation of TCO.

[1] The reliability oriented engineering software R-MES Project© (Reliability Maintenance Engineering System Project) is used for performing the above mentioned modelling and calculation steps from 4 to 6.

Table 3 Results of OEE improvements in the investigated scenarios

	Scenario A	Scenario B	Scenario C
Delta OEE	+4.52 %	+0.73 %	+2.58 %

After evaluating the TCO for the as-is situation of the plant, a number of alternative scenarios has been defined (configuration/management alternatives) and the corresponding performance and cost models have been developed, thus allowing the calculation of the related TCO values.

4.3 Analysis of Alternative Scenarios

The implementation of the methodology resulted for the company as a useful approach in order to identify and support re-configuration decisions. The company identified three main potential alternative configuration scenarios of the production line and the methodology allowed evaluating the benefits in term of savings along the lifecycle of the system by the estimation of the differential TCO.

More in detail, the scenarios that have been proposed by the company asset managers for comparative evaluations are the following:

- Scenario A: the installation of a second machine of type E to be kept in stand-by with the already existing one;
- Scenario B: the disposal of the mechanical transport machine N and its substitution with a pneumatic transport system;
- Scenario C: The installation of three more screens in stand-by to the existing ones.

After implementing the methodology for the as-is situation and the three alterative ones, the technical outputs in terms of OEE (that are showed in Table 3) have been used to make the economic evaluation by combining them with the related cost inputs.

In particular, for each scenario, the differential costs and savings with respect to the as-is situation have been considered (such as, energy consumption, acquisition and installation costs, end of life disposal cost for the new equipment etc.), as well as the additional margin resulting from the increase in production volume.

After establishing a lifetime period for the evaluation of the various scenarios, the TCO cost calculation model allowed the company estimating the money cash-flow over the asset lifecycle and the payback time related to the investment required by each scenario. These data are not presented due to confidentiality reasons, however the results were very promising and attracted the attention of the company management asking for a more detailed estimation work.

4.4 Benefits and Limitations

After the case was developed and results generated, the plant management confirmed the usefulness of the model as a tool for supporting investment decisions by proving the return of an investment taking into account the life of the asset and its performance along it, going beyond the pure acquisition cost. The use of RAMS modeling techniques combined with Monte Carlo simulation engine provided a fast way to evaluate trade-offs among availability and redundancy. It resulted that performance analysis and reliability engineering are fundamental for financial and economic evaluations referring to capital-intensive asset systems. During the development of the case some criticalities emerged that need to be overcome in the future. In particular, the main limit was found at the data acquisition step. In fact, data regarding the past failures and repair events where spread among different sources and not complete to be used. This limit was overcome through the use of estimations asked to the plant experts of TBF and TTR values. The estimations allowed building triangular distributions for the two variables for each component to be used for the simulation. Anyways, it is evident that a reliable and complete historical data base would have made the calculations more precise through a fitting of the distributions over the real data.

5 Conclusions

TCO is seen a useful indication for guiding asset managers in the decision making process by companies and the main value is that it is a synthetic economic value including in itself a lifecycle vision and technical evaluations. TCO can be used as a management decision tool for harmonizing the never ending conflicts by focusing on facts, money, and time [5] and, if properly estimated it does represent a competitive advantage for companies.

Up to day, there are still a number of difficulties that limit a TCO model widespread adoption by industry and there is no single model that has been accepted as a standard. As it is pointed out by [1] the desire to implement life cycle costing was much talked about but little practiced. This can be attributed to several major obstacles which also emerged through the application case: (i) absence of a database and systematic approach to collect and analyze the significant amount of information generated over the life of projects [37], (ii) general lack inside the organizations of the adequate consideration of the entire asset life cycle that requires inter-functional cooperation and alignment [2, 3, 22], (iii) establishment of the more appropriate modelling approach for evaluating the technical performances of the asset over its lifecycle by accordingly generating the asset failure, repair and operation events.

The research work presented in this paper is following these issues moving in the direction of integrating technical performance and cost models so to be able to develop a realistic evaluation of the TCO of an asset over its estimated lifecycle. By using simulation together with RBD modeling of the system under study, allows to easily evaluate the technical performances of production systems in a computer environment.

On the other hand, the use of an appropriate cost model can support management in a decision making process which is oriented to the whole asset life cycle. This approach allows combining the reliability engineering concept to the economic and financial evaluation of investments translating them into the money-language which is essential to make the connection between asset management and profitability. Future research must include in the models also intangibles problems that are not necessarily related to production losses, but that lead to costs for the company. Moreover, more case studies may be developed to make the methodology generalizable.

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