Chapter 1
Application of a performance - driven TCO evaluation model for physical asset management

Irene Roda[1], Marco Garetti[1]

Abstract The core concept of this paper is the total cost of ownership (TCO) of industrial asset and its relevance in supporting decision making if properly evaluated through the analysis of the asset technical performances. The paper is based on a framework that systematizes the benefits and potential applications of a TCO for different kind of stakeholders at different stages of the life cycle of the asset and for supporting different kind of decisions. The aim is to present an experimental case study that has been implemented 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 relevant gap that still exists 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 the 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. The objective of the proposed approach is to overcome the above mentioned limitations that are among the main obstacles for a spread application and use of TCO models in decision making for asset management.

1.1 Introduction

In order to meet the challenges of global competition and changing market conditions, production companies need to adopt an asset management strategy and the core issue of physical assets management should be how to sustain or improve the life cycle profits of the original investment (Komonen et al., 2006). With this regard, one of the challenges in the physical asset management field is to keep a

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[1] I. Roda, M.Garetti (✉)
Politecnico di Milano, Department of Management, Economics and Industrial Engineering,
Via Lambruschini 4/b, 20156 Milano – Italy
e-mail: irene.roda@polimi.it, marco.garetti@polimi.it

life cycle perspective whenever an action must be taken for any asset both for acquisition / configuration decisions and management decisions. 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 a supporting evidence that allows informed decision-making (Parra et al., 2009).

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 (Woodward, 1997). 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 (Lad and Kulkarni, 2008; Thiede et al., 2012). Moreover (Clarke, 1990) and other authors later on, gave it a more strategic connotation than the general concept of LCC, giving it the meaning of a supporting information for strategic choices regarding both investment decisions and operational strategies.

1.1.1 TCO applications and benefits

It is widely accepted in the academic literature (Schuman and Brent, 2005) that TCO should be an integral part of an asset management strategy and the same is assessed by the existing normative within the field, such as the ISO 55000 series of standards for asset management (ISO 55000:2014(E), 2014). 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 [(ISO 55001:2014(E), 2014); Section 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 to convey the information it represents not only to people within the manufacturing unit in question, but also to people in other parts of the organization, such as company management or outside the company, such us costumers / suppliers (Al-Hajj & Aouad, 1999; Fleischer, Weismann, & Niggeschmidt, 2006). In fact, the ability to effectively identify cost drivers and manage cost reductions is a competitive advantage for companies (Heilala et al., 2006).

This work will refer to the framework (in Table 1.1) that the authors developed based on an extensive literature review aiming at highlighting which are the potentialities for a company of having a model / tool that allows evaluating the TCO of industrial assets.

Table 1.1 Framework of TCO utility for asset providers / users

	ASSET PROVIDER		ASSET USER	
	Configuration	Management	Configuration	Management
BOL	- Evaluation of project alternatives - Comparison and optimization of design alternatives - Components / equipment procurement and construction alternatives evaluation - spare parts requirements estimation. [1], [2], [3], [4]	- Communicating value to the customer and selling - Propose the clients specific design solutions - Pricing - Contracting maintenance service provision [1], [2], [4] , [5]	- Evaluation of design alternatives offered by provider [6]	- Suppliers and tenders evaluation & selection - Maintenance service contract evaluation - Investment, budget planning, cost control [2], [7], [8], [4], [9]–[11]
MOL	- Proposal of reconfiguration solutions	- Maintenance service provision offering - Spare parts provision offering	- Reconfiguration decisions - WIP sizing [12], [13]	- Maintenance scheduling and management - Repair level analysis - Asset utilization and production strategies (Barringer, 2003; Korpi and Ala-Risku, 2008), (Lad and Kulkarni, 2008)
EOL	- Proposal of reconfiguration for EoL optimization	- Evaluation and proposal of rehabilitation strategies	- Reuse strategies for components / machines	- Evaluation of rehabilitation strategies [3], [16], [11]

References in the framework	
[1] Carpentieri and Papariello, 2006	[9]Denkena, et al., 2006
[2]Korpi and Ala-Risku, 2008	[10]Thiede, et al., 2012
[3]Asiedu and Gu, 1998	[11]Waghmode and Sahasrabudhe, 2012
[4]Schuman and Brent, 2005	[12]Tomasella and Parlikad, 2012
[5]Snelgrove, 2012	[13]Arata and Arata, 2013
[6]Fabrycky and Blanchard, 1991	[14]Lad and Kulkarni, 2008
[7]Rühl and Fleischer, 2007	[15]Barringer, 2003
[8]Ellram and Siferd, 1998	[16]K. Shahata and T. Zayed, 2008

In particular, three main dimensions have been identified within the framework:

1. type of stakeholder: given the meaning itself of TCO, it is evident that asset users are the main stakeholders (industrial equipment or plant owners / managers); nevertheless asset providers (industrial equipment or plant builders / manufacturers) have also interest in evaluating the TCO of assets they build / sell. Each of the two types have some common and some distinguishing reasons why they are interested on being able to evaluate the TCO of industrial assets, and this is highlighted in the framework;
2. type of supported decision: a TCO model has potentiality to support different kinds of decisions and in the framework two main categories have been identified: (i) configuration decisions and (ii) management decisions. The first category includes all those decisions that have direct influence on the physical configuration of the asset, while the second one refers to those decisions that deal with the management and operation of the asset and of the management of the processes around the asset (marketing, purchasing, usage, etc.).
3. phase of the life cycle: TCO analysis is preferably carried out in any and all phases of an asset's life cycle to provide input to decision makers (Kawauchi and Rausand, 1999; Schuman and Brent, 2005). In the following framework the involvement of the two different types of stakeholders is considered at each phase of the life cycle, and it is evident that it differs depending on the phase.

The framework represents which is the utility that 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).

1.2 Problem statement and objective

Even if it is commonly assessed that the evaluation of TCO has a positive effect on cost control, management strategy selection, quality optimization and best cost-effectiveness management; however, most of the proposed TCO methods up to day only consider the cost but neglect the performance of the system, which have significant limitations (Chen et al., 2013). 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 there is the need of including system performance characteristics like system availability, in upfront decisions for achieving the lowest long term cost of ownership (Clarke, 1990; Kawauchi and Rausand, 1999; Woodward, 1997).

Some main issues have to be considered when approaching the TCO evaluation of a production system as a support for investment decisions:

1. a large number of variables directly and indirectly affect the real costs 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.) (Durairaj et al., 2002; Parra and Crespo, 2012);

2. 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 (Saleh and Marais, 2006);
3. complex relationships in the assets intensive system dynamics due to presence of many coupled degrees of freedom that make it not easy to understand the effects of local causes on the global scale. In fact, the interdependencies between various subsystems might create additional costs and differences in life span and upgrade characteristics (Xu et al., 2012);
4. conventional cost accounting fails to provide manufacturers with reliable cost information due to the inability of counting so-called invisible and, in particular, intangible costs, and thus there is inaccuracy in calculating total costs (Chiadamrong, 2003).

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 & performance evaluations to generate informed decisions (Shahata and Zayed, 2008). The objective of this paper is to present a comprehensive methodology for the evaluation of the 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.

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. Based on the first experimental findings of the methodology implementation an industrial case study is presented to demonstrate the relevance and potentialities of such approach for the company.

1.3 Performance-driven TCO evaluation methodology

The TCO evaluation methodology, presented in this paper, is based on the idea that only by the integration of a performance model and a cost model it is possible to develop a reliable TCO model to be used for supporting strategic decisions (see Figure 1.1). 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.

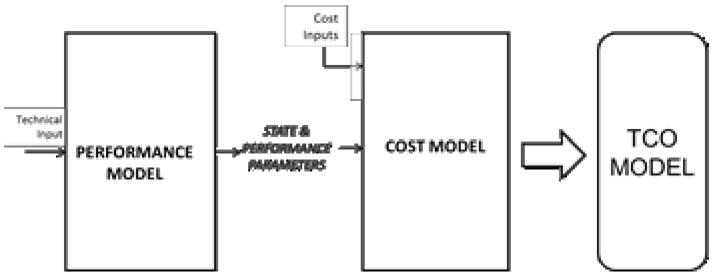

Fig. 1.1 Concept of integrated TCO evaluation model

Cost model:

The cost elements of interest in a TCO model are all the cash flows that occur during the life of the asset. Whilst there is general agreement that all costs should be included, opinion varies as to their precise identification (Woodward, 1997). 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 cost categorizations, in the end the detailed costs of each component will depend upon the particular project or system under consideration and a CBS (Cost break down structure) approach is usually adopted (Asiedu and Gu, 1998; Kawauchi and Rausand, 1999). 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 (Woodward, 1997). A relevant issue that must be taken into account is the need to include within the cost model those costs element that depends on the performance of the system. In fact, it is widely accepted that the most relevant part of TCO is related to the O&M phase and what has to be considered is that when an asset fails in the field, the cost is not limited to the cost of repair or replacement (in terms of manpower and material), but it must also include the money lost because the asset is out of service (Waghmode and Sahasrabudhe, 2012). The same is valid for other performance losses consequences (ex. quality losses, speed losses etc.). To this regard, a widely used performance measure in the manufacturing industry is overall equipment effectiveness (OEE), originally introduced by (Nakajima, 1988) (Jönsson et al., 2013). 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 as an indicator required for competitiveness analysis (Jabiri and Jaafari, 2005). The following Figure 1.2 shows which are the losses that have been considered into the cost model by referring to OEE. Availability, performance and quality losses must be considered in the OPEX (see Table 1.2) evaluation of assets and their evaluation needs technical analysis that is made by the performance model presented in the next section.

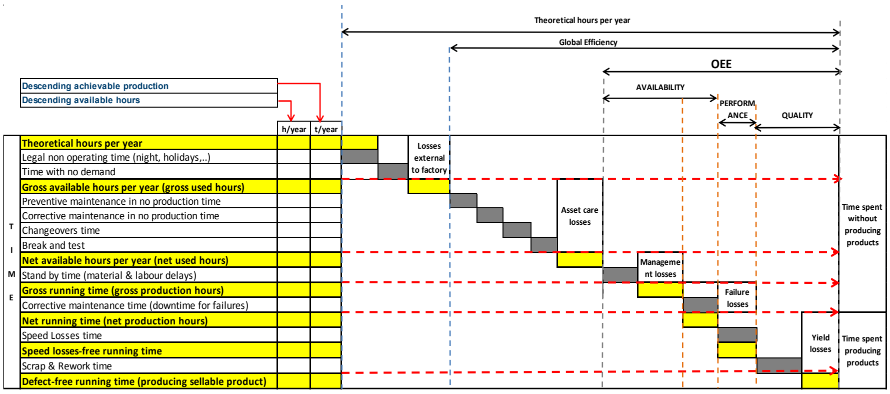

Fig. 1.2 Outline of losses and OEE calculation scheme

Globally, the following cost items are considered in the proposed cost model:

Table 1.2 Cost categories in TCO cost model

SUMMARY OF COSTS per category	
CAPEX	**OPEX**
1. Purchasing price	1. Energy Cost
2. Installation fixed cost	2. Line operators Labor Cost
3. Civil Works cost	3. Maintenance visible cost
4. Commissioning cost	3.1. Maintenance Personnel cost
5. Extra cost	3.2. Spare Parts cost
6. Installation labor cost	4. Losses related costs
	4.1. Management losses costs
	4.2. Corrective maintenance downtime losses costs
	4.3. Speed losses costs
	4.4. Non-quality costs
	4.5. Labor Savings
	END OF LIFE COSTS & SAVINGS
	1. Decommissioning costs

Performance Model:

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 (Jonsson and Lesshammar, 1999; Muchiri and Pintelon, 2008; Muthiah and Huang, 2007); and the latters introduced the term overall throughput effectiveness (OTE) as a 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 (Thiede et al., 2012). Within this second perspective, some works have been proposed in literature suggesting the use of stochastic point process (Karyagina et al., 1998; Lad and Kulkarni, 2008; Parra and Crespo, 2012) and some others propose the use of simulation based on the Monte Carlo technique (Heilala et al., 2006; Rühl and Fleischer, 2007; Shahata and Zayed, 2008). 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 (Figure 1.3).

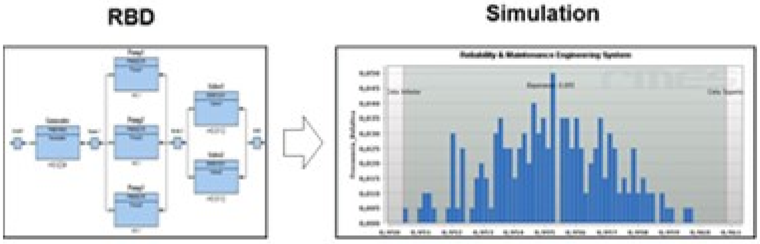

Fig. 1.3 Tools for the performance evaluation model

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. Then 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 (Kawauchi and Rausand, 1999). To this regard, new approaches are introducing the use of some conventional modeling techniques such as RBD or FTA for simulation purposes (Macchi et al., 2012; Manno et al., 2012; Roda et al., 2013). 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 application, different 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 by using the Monte

Carlo simulation and the RBD system modeling. The 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 component within the cost model (Table 1.2). 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.

1.4 Application Case

1.4.1 Introduction

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 Figure 1.4 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 prove the main potentialities of using an appropriate TCO model for supporting investment and management decisions.

Basing on the framework presented in section 1.1.1, the case refers to the *user* perspective 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. These aims confirm what is in the framework, and the focus is on the configuration decisions: reconfiguration decisions / new acquisition investments (Tomasella and Parlikad, 2012).

1.4.2 TCO evaluation procedure

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

Technical phase:

- STEP 1. Production process understanding and main system's components identification.
- STEP 2. Identification of the relevant failures modes or stop causes for each component.
- STEP 3. Reliability, maintenability and operation data acquisition
- 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 equipment 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[2]. Such data was used as one of the inputs for the following cost modelling phase.

Cost phase:

- STEP 7. Cost model setting
- STEP 8. Cost data acquisition
- STEP 9. Calculation of TCO

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 technical and cost models have been developed, thus allowing the calculation of the related TCO values.

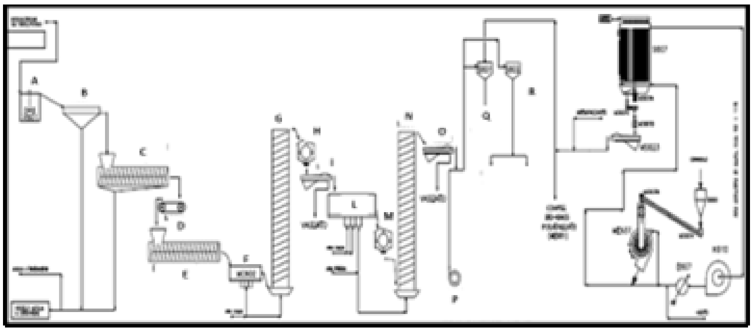

Fig. 1.4 The case-study production line

1.4.3 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 alternatives for the production line and the methodology allowed to evaluate 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.

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[2] 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.

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 1.3) have been used to make the economic evaluation by combining them with the related cost inputs.

Table 1.3 Results of OEE improvements in the investigated scenarios

	Scenario A	Scenario B	Scenario C
Delta OEE	+ 4,52 %	+ 0,73 %	+ 2,58 %

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 to estimate 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.

1.4.4 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 tried to be overcome through the use of estimations by the plant experts of TBF and TTR values that allowed to build 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.

1.5 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 (Barringer, 2003) and, if properly estimated 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 (Al-Hajj and Aouad, 1999) 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 (Woodward, 1997), ii) general lack inside the organizations of the adequate consideration of the entire asset life cycle that requires inter-functional cooperation and alignment (Amadi-Echendu, 2004; Amadi-Echendu et al., 2010; Markus and Werner, 2012), 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 Total Cost of Ownership 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 for OTE estimation must include quality problems that are not necessarily related to production losses, but that lead to costs for the company.

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