Production Planning & Control
The Management of Operations

ISSN: 0953-7287 (Print) 1366-5871 (Online) Journal homepage: www.tandfonline.com/journals/tppc20

Building a Total Cost of Ownership model to support manufacturing asset lifecycle management

Irene Roda, Marco Macchi & Saverio Albanese

To cite this article: Irene Roda, Marco Macchi & Saverio Albanese (2020) Building a Total Cost of Ownership model to support manufacturing asset lifecycle management, Production Planning & Control, 31:1, 19-37, DOI: 10.1080/09537287.2019.1625079

To link to this article: https://doi.org/10.1080/09537287.2019.1625079

PRODUCTION PLANNING & CONTROL
2020, VOL. 31, NO. 1, 19–37
https://doi.org/10.1080/09537287.2019.1625079

Building a Total Cost of Ownership model to support manufacturing asset lifecycle management

Irene Roda[a], Marco Macchi[a] and Saverio Albanese[b]

[a]Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milano, Italy; [b]Versalis S.p.A, San Donato Milanese, Milano, Italy

ABSTRACT
This paper proposes a methodology to build a Total Cost of Ownership (TCO) model aimed to support decision-making for manufacturing asset lifecycle management. Existing challenges for TCO adoption in industry are identified through literature review and through an explorative multiple case study involving eight manufacturing companies. Based on it, a general methodology is proposed for building a novel asset-centric performance-driven TCO model. The methodology is based on an integrated modelling approach that puts together technical performance analysis and economic analysis, enabling the asset users linking their knowledge about asset performance with offers specifications by the asset providers. In this way, the TCO model becomes a decision-making tool for the asset users that can also guide the relationship with providers. An application case within a chemical production company is described, showing how challenges are addressed through the proposed methodology, within a real context.

ARTICLE HISTORY
Received 22 October 2018
Accepted 30 April 2019

KEYWORDS
Total Cost of Ownership; life cycle cost; manufacturing; asset life cycle management; product-service systems

1. Introduction

Total Cost of Ownership (TCO) is a well-known cost modelling tool within the Supply Chain Management field (LaLonde and Pohlen 1996; Trienekens and Beulens 2001). Traditionally, TCO is conceived mainly as a purchasing tool supporting products/systems users in the vendors selection process (Ellram 1995; Ellram and Siferd 1998; Caniato et al. 2014). As such, its adoption is advocated both in B2C and B2B settings, primarily to products/systems within the electronic industry, the military sector and the heavy equipment industry (Saccani, Perona, and Bacchetti 2017).

Nevertheless, in recent years, TCO is getting more and more recognized as a strategic tool for lifecycle management of products/systems, under a wider perspective than the traditional one. Its role is enlarged along the whole lifecycle of the products/systems, as a support for taking different kinds of decision, both investment and operational ones (Thiede, Spiering, and Kohlitz 2012; Schuman and Brent 2005; El-Akruti, Dwight, and Zhang 2013; El-Akruti et al. 2015; Chen and Keys 2009). With this regard, the recently published body of standards on Asset Management (ISO 55000:2014(E) 2014) reinforces the new interest towards an extended scope of work for TCO, indicating that: '[…] 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 55000 – Section 6.2.2.4].

It is worth, then, renovating the investigation on TCO, to discover if new understanding and needs in industry emerge, extended to the lifecycle management of products/systems. This research is developed in this scope, and it focuses on the management of industrial assets, with specific concern on manufacturing assets.

Moreover, in recent years, TCO is discussed and considered as a tool that can support the development of Product-Service Systems (PSSs), through the so-called TCO-based contracts (Bonetti, Perona, and Saccani 2016; Datta and Roy, 2010; Lanza and Rühl 2009; Roy et al. 2016). In fact, with the rapid and disruptive changes in the market and in production, the asset users are getting more and more willing to work with the Original Equipment Manufacturers (OEMs)/providers (Ferrin and Plank 2002), and TCO is considered as a neutral tool to assess costs and benefits embedded in business-to-business transactions (Caniato et al. 2014). This trend confirms the relevance of the TCO and the need to investigate its development and use as a lifecycle management supporting tool.

This paper aims at identifying the existing challenges for TCO adoption, keeping the perspective of asset users. First, a literature review and, afterwards, an explorative multiple case study involving eight manufacturing companies are carried out. Based on the outcomes, a general methodology is proposed for building a novel asset-centric performance-driven TCO model that levers on the asset system performance knowledge by the asset users. The aim is to build a TCO model as decision-making tool for the asset users to support asset management. Moreover, the model is intended to also guide the relationship (i.e. communication and

CONTACT Irene Roda irene.roda@polimi.it Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, Milano 20133, Italy

collaboration) with providers, primarily in terms of purchasing contract specifications. In fact, the proposed TCO model allows the asset users linking their knowledge about asset performance with offers specifications by the asset providers, through technical performance analysis (of the assets of interest).

The paper is organized as follows. Section 'State of the art' provides the findings of the literature review on the adoption of TCO models to support decisions and on the applicability challenges in practice; Section ' Evidence from industry through multiple case study' presents the findings of the multiple case study, refining the identified challenges. Based on it, in Section 'TCO model building methodology' the requirements for a TCO model as a strategic tool for lifecycle management of manufacturing assets are defined, and the methodology for TCO model building is proposed. Section 'Application case study' describes an application case within a chemical production company, showing how challenges are addressed through the proposed methodology. Finally, Section 'Conclusions' is dedicated to the conclusions.

2. State of the art

2.1. TCO concept

In the literature, the concept of TCO is strictly related to the concept of Life Cycle Cost (LCC) and a clear separation of the two is often missing (Gram and Schroeder 2012). In many publications, the two terms are used without distinction and it is often stated that the objective of LCC is to enable choosing the alternative leading to the lowest 'cost of owning' the asset (Taylor 1981; Clarke 1990; Barringer and Weber 1996; Kawauchi and Rausand 1999). Nevertheless, several authors give TCO a different meaning with respect to LCC declaring that it provides a selected perspective on LCC, focusing on the user's perspective of the considered asset (Carrubba 1992; Thiede, Spiering, and Kohlitz 2012; Gram and Schroeder 2012; Lad and Kulkarni 2008; Kumar et al. 2006; Saccani, Perona, and Bacchetti 2017). Moreover, some authors underline the strategic connotation of TCO comparing to the general concept of LCC, giving to TCO the meaning of a supporting information for strategic choices regarding both investment decisions and operational strategies (Clarke 1990; Thiede, Spiering, and Kohlitz 2012).

Based on the different definitions that can be found in the literature, for the scope of this research, the TCO is defined as the sum of all significant costs associated with an asset over its life cycle, to support the asset-related decision-making for lifecycle management. This definition is confirmed by the findings collected through the literature review and the multiple case study that are described in the reminder of this section and in Section 'Evidences from industry through multiple case study'.

2.2. A review of TCO models in the literature

Extensive reviews about TCO can be found in the works by Waghmode and Sahasrabudhe (2012), Gram and Schroeder (2012), Korpi and Ala-Risku (2008) and Saccani, Perona, and Bacchetti (2017). In this research, a more focused review was undertaken by identifying models that specifically refer to industrial assets. Starting from over 1700 papers resulting from a search in the SCOPUS and ISI Web of Knowledge database using the keywords: 'Total Cost of Ownership' and 'Life Cycle Cost(ing)', we selected 281 papers that: (i) are written in English and, (ii) belong to research subject areas related to engineering, business and decision-making (excluding medicine, nursing and other areas out of the scope). Most of the papers in the sample (47%) were published from 2011 onwards, testifying to the increased interest in the topic by researchers in recent years. Based on the subset of 281 papers, we then selected 16 papers that (iii) develop AND apply empirically TCO models, (iv) address manufacturing assets as complex industrial assets. We then analysed each model by studying:

- decisions and decision makers, i.e. (i) which kind of decisions the TCO model is conceived to support and, (ii) for which decision maker,
- performance analysis integration and uncertainties consideration, i.e. (i) whether the TCO model is based on technical performance analysis to quantify the cost items that are affected by the asset performance; and (ii) if and how the asset-related uncertainties are included in the performance analysis,
- performance analysis asset level application, i.e. for which asset (single component or system) the TCO model is developed and the performance analysis, if integrated in the cost model, is implemented.

Based on the analysis, three main findings have been deducted and they are detailed hereafter.

Finding 1: TCO can be used for different kinds of decision along the lifecycle of the assets by both asset users and asset providers

Reviews on the TCO topic (Saccani, Perona, and Bacchetti 2017; Caniato et al. 2014) state that most TCO models in the literature are developed for supporting the vendor selection process, and this was confirmed by our research when analysing the complete set of 281 papers. Nevertheless, when focusing on the selected 16 models (Table 1), it is interesting to observe that some of them are developed not only for vendor selection, but also for asset configuration (Mandolini, Marilungo, and Germani 2017; Ramadan 2014; Lad and Kulkarni 2008; Heilala, Helin, and Montonen 2006) and contract definition with suppliers (Bonetti, Perona, and Saccani 2016; Lad and Kulkarni 2008), from the asset users' perspective. Besides, some works highlight the potentialities to use a TCO model for the asset providers/OEMs as well, to support the asset design stage (Chen and Keys 2009; Enparantza et al. 2006) and the contract definition process (Carpentieri and Papariello 2006; Fleischer, Wawerla, and Niggeschmidt 2007; Lad and Kulkarni 2008). Finally, some contributions are also developed for supporting asset operations decisions by

Table 1. TCO models in literature: decisions and decision makers.

		Decisions			
Paper	Decision-Maker	Vendor selection/procurement	Asset configuration/design	Contract definition	Operations
Mandolini, Marilungo, and Germani 2017	User	X	X		
Bonetti, Perona, and Saccani 2016	User	X		X	X
Kanagaraj et al. 2016	User	X			
Landscheidt and Kans 2016	User	X			X
Caniato et al. 2014	User/OEM	X			X
El-Akruti et al. 2015	User				X
Ramadan 2014	User	X	X		
Parra and Crespo 2012	User	X			
Thiede, Spiering, and Kohlitz 2012	User				X
Chen and Keys 2009	OEM		X (for offer phase)		
Lad and Kulkarni 2008	User/OEM		X	X	X
Fleischer, Wawerla, and Niggeschmidt 2007	OEM			X	
Hwang, Bae, and Cho 2007	User				X
Heilala, Helin, and Montonen 2006	User		X		
Carpentieri and Papariello 2006	OEM			X	
Enparantza et al. 2006	OEM		X (for offer phase)		

the asset users (maintenance, utilization, etc.) (Bonetti, Perona, and Saccani 2016; Landscheidt and Kans 2016; Caniato et al. 2014; Thiede, Spiering, and Kohlitz 2012; El-Akruti et al. 2015; Hwang, Bae, and Cho 2007; Lad and Kulkarni 2008). This confirms the relevance of TCO for supporting asset-related decision-making at different stages of the asset lifecycle. Indeed, it extends what was already emphasized in a previous review by Roda and Garetti (2014), precursor of the present work.

Finding 2: Performance analysis comprising asset-related uncertainties is required within a TCO model

In the literature, it is recognized that a TCO model should take into account that, when the asset fails, the cost of repair/replacement (in terms of manpower and material) is affected, but also the money lost because the asset is out of service may have to be quantified (Waghmode and Sahasrabudhe 2012; Roda and Garetti 2015). The same is valid for other unexpected performance decay consequences like quality losses, speed losses, etc. To this regard, Parra and Crespo (2012) identified the following losses: (i) opportunity losses/deferred production, (ii) production losses (unavailability), (iii) operational losses, (iv) impact in the quality, (v) impact in security and environment. Overall, the term hidden costs is often used to refer to the cost items affected by these losses (Gungor and Evans 2017). When analysing the selected works, most of the proposed TCO models (14 out of 16) include the hidden costs within the proposed Cost Breakdown Structure (CBS) (Table 2).

Most of the works considering the hidden costs within the proposed TCO model, remark the need to address the uncertainty due to failures occurrence and performance decays characterizing any asset's behaviour during its lifecycle; thus, hidden costs are looked as probabilistic cost items (Sinisuka and Nugraha 2013; Clarke 1990; Woodward 1997).

More in detail, the majority (11 out of 14) of the works proposing the inclusion of the hidden costs in the TCO also propose a quantitative approach for integrating the uncertainty related to the asset performance, within the cost evaluation (Table 2). Quantitative models are typically based on mathematical relationships to describe certain characteristics (e.g. reliability, availability, …) of an asset under certain conditions/assumption (Waghmode and Sahasrabudhe 2012). In particular, two quantitative approaches can be identified (Kawauchi and Rausand 1999; Thiede, Spiering, and Kohlitz 2012): (i) ex-post calculation, based on historical or actual data, or (ii) ex-ante estimation, aiming at a static or dynamic prediction of total costs through costs rates and estimated behaviour over the life cycle.

Table 2. TCO models in literature: performance analysis.

Paper	Hidden costs	Performance analysis
Mandolini, Marilungo, and Germani 2017	NO	NO
Bonetti, Perona, and Saccani 2016	NO	NO
Kanagaraj et al. 2016	YES	YES (ex post)
Landscheidt and Kans 2016	YES	NO
Caniato et al. 2014	YES	NO
El-Akruti et al. 2015	YES	YES (ex post)
Ramadan 2014	YES	YES (ex post)
Parra and Crespo 2012	YES	YES (ex ante)
Thiede, Spiering, and Kohlitz 2012	YES	YES (ex ante)
Chen and Keys 2009	YES	YES (ex post)
Lad and Kulkarni 2008	YES	YES (ex post)
Fleischer, Wawerla, and Niggeschmidt 2007	YES	YES (ex ante)
Hwang, Bae, and Cho 2007	YES	YES (ex ante)
Heilala, Helin, and Montonen 2006	YES	YES (ex ante)
Carpentieri and Papariello 2006	YES	YES (ex post)
Enparantza et al. 2006	YES	NO

Looking at the selected models (Table 2), some of them use the ex-post estimation based on statistical analysis from operation records (El-Akruti et al. 2015; Chen and Keys 2009; Ramadan 2014; Carpentieri and Papariello 2006; Lad and Kulkarni 2008; Kanagaraj, Ponnambalam, and Jawahar 2016). This is easier and faster to apply; however, it relies on the availability of appropriate data, and it cannot be used for the evaluation of new solutions (Chen and Keys 2009).

The other models propose stochastic/probabilistic methods for ex-ante estimation. In their work, Parra and Crespo (2012) use the minimal repair approach ('as-bad-as-old' repairs) through superimposed renewal process and non-homogeneous Poisson process (NHPP), as a solution to evaluate the economic impact of the failure in the life cycle cost analysis. In their work, Fleischer, Wawerla, and Niggeschmidt (2007) use Monte Carlo simulation to propose a life cycle cost estimation focused on the maintenance costs.

The authors assess the potentialities of simulation compared to statistical convolution by stating that, through it, modelling is flexible to easily simulate the life and to evaluate the performances of potentially different system configurations. Thiede, Spiering, and Kohlitz (2012) propose a dynamic TCO calculation model based on Monte Carlo technique and the machine state charts while focusing on injection moulding machines and on maintenance costs and energy consumption issues. Heilala, Helin, and Montonen (2006) present a methodology for an assembly system design evaluation; they use system life cycle modelling and a TCO analysis integrating Overall Equipment Efficiency (OEE), Cost of Ownership and component-based simulation methods. Finally, Hwang, Bae, and Cho (2007) propose a performance evaluation model based on simulation modelling joined with manufacturing system configuration, reliability, availability and maintainability (RAM) analysis, and LCC. Overall, it emerges that the use of simulation is majorly supported as it has got many potential advantages, like the high precision in predictions (Kawauchi and Rausand 1999). Nonetheless, a critical aspect is given by the complexity characterizing the industrial systems themselves that makes their modelling and analysis a non-trivial task (Manno et al. 2012). Indeed, 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).

Finding 3: Performance analysis at system level is required within a TCO model

Most of the analysed TCO models (Table 3) are commonly focused on individual equipment or components and there is no consideration within the model about the behaviour of the asset system in its entirety; thus, the impacts at the system level, as combination and interactions between asset components, are rarely considered. This is probably due to the fact that the complex relationships characterizing the manufacturing systems dynamics make it not easy to understand the effects of local events on the global scale of the system (Xu, Elgh, and Erkoyuncu 2012) in terms of performance decays consequences and subsequent costs.

Heilala, Helin, and Montonen (2006) consider modelling as a necessary technique to be able to properly estimate the TCO of an assembly system to support its configuration. Nevertheless, the authors declare that the proposed model in their work best applies at workstation level while for including system-level analysis, this can be done only by creating a model for each machine and letting the user manually collating the data at the assembly-line level. Carpentieri and Papariello (2006) propose a model and architecture for LCC analysis for automotive systems, nevertheless, the paper does not clear out if the impact of local decisions can be evaluated on the TCO at system level. Ramadan (2014) introduces a model for selecting the suppliers of the different components constituting a series system using TCO. The approach is analytical, and it may become complex for real applications to industrial asset systems. Interesting findings come from the work by Hwang, Bae, and Cho (2007) that introduces a four-step generative performance evaluation model for a manufacturing system based on the RAM modelling theory to consider the system availability and life cycle cost in system performance evaluation.

Overall, it is apparent that proposing a TCO model that is based on technical performance analysis at system level is rarely proposed and, when this is done, the established approaches suffer from some gaps, probably due to the inherent complexity of system modelling and analysis. Indeed, based on the evidences collected by this focused review on manufacturing assets, it can be said that almost no TCO model that has been proposed so far implements performance analysis at system level to estimate the hidden costs.

Nevertheless, it is recognized that, in order to have a robust AM process, the systemic effect of any local decision has to be considered in decision-making (Roda and Macchi 2018), hence, it is necessary when estimating TCO to quantify the so-called hidden costs at system level and not only at component level.

2.3. TCO models in the international standards

Looking at the standardization status of Total Cost of Ownership or Life Cycle Cost, there are several existing

Table 3. TCO models in literature: asset level application.

	Object	
Paper	Equipment/component	Asset system
Mandolini, Marilungo, and Germani 2017	X (Printing machine)	
Bonetti, Perona, and Saccani 2016	X (Melting furnace)	
Kanagaraj et al. 2016	X (Generic component)	
Landscheidt and Kans 2016	X (Industrial robot)	
Caniato et al. 2014	X (Colourant dispensing machines)	
El-Akruti et al. 2015	X (Lining in Electric Arc Furnaces)	
Ramadan 2014		X (Manufacturing system)
Parra and Crespo 2012	X (Compression system in O&G, Locomotive in rail freight industry)	
Thiede, Spiering, and Kohlitz 2012	X (Injection moulding machines)	
Chen and Keys 2009	X (Heavy equipment)	
Lad and Kulkarni 2008	X (Machine tool)	
Fleischer, Wawerla, and Niggeschmidt 2007	X (Generic component)	
Hwang, Bae, and Cho 2007		X (Manufacturing system)
Heilala, Helin, and Montonen 2006		X (Assembly system)
Carpentieri and Papariello 2006		X (Assembly system)
Enparantza et al. 2006	X (Machine tools)	

Table 4. TCO models applicability challenges from the literature.

Paper	Input data		Model implementation and use			Company Culture
	Absence of a database and systematic approach to collect data	Lack of reliable past data	Difficult implementation (cash constraints, time constraints, …)	Difficult assumptions for future cost estimates and predictions/uncertainty of forecasting	Lack of universal methods and standard formats for calculating TCO	Tendency towards short term perspective in decision-making
Bouachera et al. 2007	X	X		X		X
Boussabaine and Kirkham, 2008)	X	X			X	
Korpi and Ala-Risku 2008		X			X	
Xu et al. 2012		X				
Schuman and Brent 2005			X	X	X	
Waeyenbergh and Pintelon 2002			X	X	X	
Emblemsvåg 2003						X

standards about the topic, but they are still very specific in term of addressed sector or too conceptual.

The IEC60300–3-3 is intended to cover any application domain and it presents a basic concept and procedure for LCC analysis. Even if it can be considered as a good reference, it is still too general (Kawauchi and Rausand 1999) and not easily adaptable to specific industries like manufacturing. The ISO 15663-2 addresses petroleum and natural gas industries offshore facility. It defines all cost elements to be analysed and provide spreadsheets to calculate the cost elements for LCC estimation. In this sense, this standard is one of the most practical ones. The SEMI E35-0618 (2018) provide standard metrics for evaluating unit production cost effectiveness of factory equipment subsystems in the semiconductor industry. The VDMA 34160 includes a comprehensive list of items influencing the cost of a machine throughout its life cycle while VDI 2884 (2006) offers a detailed choice of Life-Cycle-Costs which are subdivided into initial costs and operating costs. In the construction sector, standards addressing LCC and TCO are the ASTM E917 – 17 (2017), the ISO 15686–5:2017, and the recently published APPA 1000-1 (2018). There are also some military and public sector standards and handbooks on LCC (Korpi and Ala-Risku 2008). The NATO - ALCCP-1 (2008) is one of the main references for the military sector about it.

Overall, what emerges is that here is still no single standard accepted that can be taken as a general reference for any domain. The main criticisms in the literature are lack of reliability and validity, the lack of detail and the lack of expandability (Gram and Schroeder 2012), as it also emerges in next section about challenges for TCO applicability in practice as identified by researchers.

2.4. Challenges for TCO applicability in practice

Looking at current trends, even though TCO is not a new topic, there are still a number of challenges limiting its widespread adoption in industry (Bouachera, Kishk, and Power 2007; Woodward 1997; Korpi and Ala-Risku 2008; Landscheidt and Kans 2016). Most of the scientific works that have identified the main challenges, refer to other application objects rather than industrial assets, like building (Al-Hajj and Aouad 1999; Boussabaine and Kirkham 2008) or finished products (Emblemsvåg 2003). In detail, the main challenges for TCO adoption according to the literature are enlisted hereafter. The list was used as a reference point for the empirical investigation, described in Section 'Evidences from industry through multiple case study', on the main challenges for TCO adoption in industrial practice.

In particular, the challenges that emerged from the literature review have been grouped within three categories, which are: i) challenges related to the input data needed for the TCO model; ii) challenges related to the implementation and use of the TCO model; iii) challenges related to the culture of the company using the model. Table 4 shows the identified challenges by different authors.

The main challenges identified in the literature are related to input data and model implementation and use. In particular, the lack of reliable past data together with the absence of a database and systematic approach to collect the significant amount of information generated over the life of the assets, are considered the main challenges for TCO adoption in industry. Regarding the main challenges about TCO model implementation and use, the lack of universal methods and standard formats for calculating TCO (see Section 'TCO models in the international standards') is considered as one important challenge together with the difficulty in making assumptions for future expectations, cost estimates and predictions, as well as dealing with uncertainty of forecasting. Some authors also highlight some challenges related with the company's culture related to the difficulty in approaching decisions through a long-term perspective, highlighting the following aspects. First, the failure of owners or managers with short-term responsibility for an asset to consider effectively the longer-term impact of their decisions on the asset's operations and maintenance requirements (Bouachera et al. 2007; Emblemsvåg 2003). Second, the general wish to minimize the initial expenditures in order to increase return on investment, meet budgetary restrictions, or both (Bouachera et al. 2007). Finally, the failure of designers to be able to visualize and include life cycle cost goals in their design criteria (Bouachera et al. 2007). The identified challenges are used as a reference to implement the multiple case study and collect evidences from industry in order to corroborate these findings.

3. Evidences from industry through multiple case study

3.1. Case study design

After the analysis of the literature, an exploratory multiple case study was carried out to collect evidences about the perception on TCO adoption potentialities and challenges in practice by companies. The study targeted eight production companies in Italy (users of manufacturing assets). The selected companies belong to different industrial sectors in order to avoid biases and to cover a broader scope in terms of industry. Table 5 shows the panel of companies selected for the case study.

The main source of the primary data for this research step was a face-to-face semi-structured interview. Semi-structured interview brings the opportunity for the interviewee to share information relatively freely with the interviewer since such interviews possess some degree of flexibility in content (Bryman 2009). The interviews were all recorded digitally and each lasted around 1 h on average. The interviews protocol was composed of six open questions. It was designed addressing the main issues that were identified through the literature analysis. The chosen unit of analysis was the company from the perspective of the maintenance, technical services or industrial engineering function. The data collected from the case studies were then analyzed using a uniform approach, interpreting the transcripts according to the coding technique, in order to denote the relevant concepts emergent during the interviews (Corbin and Strauss 2014). The analysis of the interviews and the main findings allowed corroborating the findings of the literature review and defining the requirements for the TCO building methodology that is presented in Section 'TCO model building methodology'.

Overall, among the eight involved companies, only two of them declared the use of a TCO model in a systematic way to support asset-related decision-making. The rest does not have any TCO model, or have experienced projects to try to implement it but unsuccessfully. Nevertheless, the collected opinions from all eight companies enabled the recognition of both the envisioned potentialities of TCO adoption and the main perceived challenges, considering the entire experiences of the interviewees, both positive and negative ones.

3.2. Potentialities of TCO adoption to support asset-related decision-making

The case study findings let emerge the asset-related decisions for which TCO is considered to have important supporting role. The findings of the case studies show that the industry assesses the importance of a tool like TCO for supporting different kinds of decision at any stage of the life cycle of an asset, confirming the first finding of our literature review. Table 6 shows the main potentialities as identified by the different companies (from A to H) considering the lifecycle of the asset modelled into its three main stages, i.e. Beginning of Life (BOL), Middle of Life (MOL) and End of Life (EOL) (Ouertani, Parlikad, and McFarlane 2008). More in detail, the case study findings show that TCO is considered an important tool to support a wide range of decisions along the life cycle of an asset. Overall, the consensus on the

Table 5. Exploratory multiple case study: panel of analyzed companies.

Case	Type	Sector	Core business*		People interviewed
A	Large	Chemical	2010	Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics and synthetic rubber in primary forms	• Maintenance and technical materials Executive
B	Large	Appliances	2751	Manufacture of electric domestic appliances	• Site Industrial Engineering Manager
C	Large	Steel	2420	Manufacture of tubes, pipes, hollow profiles and related fittings, of steel	• Maintenance Manager
D	Large	Steel	2400	Manufacture of basic metals	• Technical Director • Maintenance Manager
E	Large	Petro-chemical	1920	Manufacture of refined petroleum products	• Maintenance Manager
F	Large	Machine tools	2849	Manufacture of other machine tools	• Technical Functions Manager
G	Large	Food & beverage	1100	Manufacture of beverages	• Global Maintenance Director • Real estate and Energy Management
H	Large	Tyre	2211	Manufacture of rubber tyres and tubes; retreading and rebuilding of rubber tyres	• Corporate Maintenance Coordinator

*Statistical Classification of Economic Activities in the European Community, Rev. 2 (2008).

Table 6. TCO adoption main potentialities: case study findings.

Lifecycle stage	Asset-related decisions	Companies A	B	C	D	E	F	G	H
BOL	Evaluation and selection of suppliers	X	X	X	X	X		X	X
	Evaluation of alternative purchasing solutions	X	X	X	X	X		X	
	Budget definition	X	X		X			X	X
	Asset design / configuration	X	X	X	X	X	X		X
	Maintenance plan definition		X	X	X	X	X	X	X
MOL	Continuous improvement			X		X	X	X	X
	Plant re-configuration		X	X	X	X	X		
	Maintenance plan re-definition			X	X			X	X
EOL	Dismission, re-use, recycling		X			X	X	X	

Table 7. Perceived challenges for TCO adoption in industrial practice: case study findings.

Category	Challenges	Companies A	B	C	D	E	F	G	H
Input data	No database and systematic data collection								
	Lack of data								
	Low quality of data from suppliers/asset providers	X						X	
Model implementation and use	Resources constraints (cash/time constraints)				X	X			
	Cost of finding the right data	X							X
	Lack of universal methods and standard formats	X		X	X	X	X		
	Difficult assumptions for future cost estimates and predictions								
Culture	Lack of top management commitment	X	X					X	X
	Short term perspective		X	X	X	X			
	Lack of maturity		X	X					X
	Lack of a normative TCO adoption obligation	X		X					X

usefulness of TCO to support decisions at the BOL stage clearly emerges. The evidence confirms what is discussed in the literature justifying the TCO as a useful tool to ensure a decision-making process at the BOL that is aware of asset operations and impacts at later stages of the life cycle (MOL and EOL). In other words, it confirms the theory that emphasizes the centrality of TCO for supporting asset design/configuration as well as vendors selection decisions during the BOL stage, considering the impacts of these decisions later on. It is interesting to point out that, in addition, there is one more area of decision-making at the BOL stage where TCO is recognized as important, i.e. the design of the maintenance plan, what can be seen as an extension of its importance in the choice of configuration and design of the plant.

Even if the spectrum of the decisions where TCO is recognized having high supporting potential is reduced in the MOL stage, nevertheless the case study findings confirm the importance of the TCO also at this stage. The importance of the TCO during the MOL stage is symptomatic of the need to ensure an integrated management in the different stages of the life of the asset. The integrated management builds on two important functions in the life cycle: systematic tracking of changes implemented during the life of the assets; and performance monitoring to understand when inefficiencies occur. This allows facilitating different kinds of decision such as continuous improvement, plant re-configuration or maintenance plan re-definition.

Finally, it is interesting to note that the support of TCO decisions at the EOL stage of the asset is not considered as relevant by four companies in the panel. However, during the interviews, it looked like their negative experiences were biasing their answers, as they were majorly recognizing the difficulty of using it at this stage, rather than its potentials.

3.3. Challenges for TCO applicability in industrial practice

The analysis of the data collected through the case study confirms some of the main challenges to the adoption of TCO in industry that were identified in the literature. Nevertheless, interesting findings emerged that lead to the integration or correction of some of the findings of the literature review.

As it is showed in Table 7, the main perceived challenges for TCO adoption in practice regard the organizational culture and the implementation of a TCO model that can be used systematically.

Overall, no obstacles are envisaged about the availability of input data that are needed to feed the TCO model, even if it is one of the main barriers identified in the literature. All interviewed people in the eight companies assessed that no problem subsists regarding such issue. This finding can be easily justified as a consequence of the adoption of Master Data Management (MDM) solutions (otherwise known as Big Data), that is becoming a reality in the manufacturing world, considering the wealth of information collected from the manufacturing facility on a daily basis (Aberdeen Group 2012). Regarding the absence of a database and systematic approach to collect the significant amount of information generated over the life of assets, the findings from the case studies go in the same direction as the previous ones. No issue is perceived about the ability of collecting the required data through proper information systems. One concern raised that was not identified in the literature, in regard to the reliability of input data if they need to be provided by the providers. In fact, a general hesitation and complain about data as they are provided by the assets providers have been assessed among the interviewees; it remarks the need to foster collaboration between asset users and asset providers for a successful use of a shared TCO model.

Second, as far as the model implementation and use concern, some challenges emerged. Five companies out of eight identified the lack of universal methods and standard formats for calculating TCO as a barrier for its adoption in their company, confirming the literature findings. Concerns emerged from a few companies regarding the need of dedicating resources for TCO analysis, given the existing cash constraints and time constraints. In relationship to the cost model, two companies perceive the finding and preparation of the right data as a costly activity that would require dedicating some resources for it. None of the companies highlighted, as challenge, the difficulty related to the assumptions that have to be made for future cost estimates and predictions.

Most of the perceived challenges emerged related to the culture of the companies. In fact, most of the interviewees believe that the aspect that mainly inhibits the adoption of a TCO model is the spread short-term perspective adopted when approaching a decision-making process. This was mainly explained by the tendency of managers to focus on reaching goals with fast return and the lack of tools supporting long-term decision-making process. Moreover, another issue that emerges as a challenge is the general lack of commitment of the top management that drives towards the long-term perspective direction. The general lack of maturity for being ready to adopt a TCO systematically also emerged as cultural challenge. Some of the interviewees believe their company is not yet ready to adopt a TCO model given that there is still a lack of awareness of TCO potentialities. Another raised relevant issue is about the lack of a normative framework that drives to the use of TCO as an element that inhibits its adoption: some of the interviews believe that one of the reasons why the TCO is not used in the company is because there is no obligation coming from an existing norm.

3.4. Concluding remarks

Expectations on the potentialities of TCO as a support tool by the companies involved in the case study regard a wide range of decisions during the BOL and MOL stages of the asset lifecycle. In particular, all companies agree that TCO is a tool that can be used to give greater engineering contribution to support decisions that are typically made based on a mere financial forecast. This requires that a performance model is built in the TCO model for the prediction of the performances of the manufacturing assets/systems. In doing so, the long-term impacts of the decisions can be considered more punctually, also has a particular focus on the performance losses. To date, however, a standard TCO methodology is not yet available, in order to fulfil such wishes. A contribution from scientific research appears necessary. With this regard, this research addresses the problem of defining a structured methodology to build a TCO model, with the purpose to support decisions for manufacturing asset lifecycle management.

4. TCO model building methodology

4.1. Requirements and overview of the methodology

A comprehensive methodology for building up a TCO model of manufacturing assets is now proposed. The requirements that guided its development come from the major findings of the literature analysis and the explorative multiple case study, and they are summarized in Table 8 as three main issues to be addressed.

The requirements highlight the importance of grounding a TCO model on performance models, with the purpose to include the uncertainty in asset operations as well as the complexity in asset structures. Moreover, performance models should be capable of dealing with measurement of actual/historical asset behaviours as well as with the prediction of future behaviours.

Based on these considerations, a general methodology is proposed for building a performance-driven TCO that is asset-centric. The aim is to build up a tool for decision-

Table 8. Requirements for the development of the TCO building methodology.

Requirement	Motivation
Uncertainty in asset operations has to be integrated in the TCO model.	Failures and performance decays determine the inherent uncertainty of the asset behaviour during its operations. Ageing, as a long-term physical degradation, is also an endogenous factor that leads to change the uncertainty on performance losses along time. To consider their effects, the TCO model should incorporate the operational expenditures' dependency on the uncertainty of the asset performance parameters.
Systemic performance losses during the asset operations have to be quantified in the TCO model.	An asset system (i.e. a production plant/line, composed by several equipment/components) is a complex structure where the interdependencies of the component assets can be influent on the operational expenditures. Therefore, the performance losses related to the inherent uncertainty of each component asset should be assessed at the asset system level. The TCO model should quantify the operational expenditures considering the performance losses at the system level, i.e. hidden costs quantifying the systemic performance losses.
Costs have to be quantified, in the TCO model, through an ex-post and an ex-ante approach, to support both monitoring and planning tasks over the life cycle of the assets.	The technical performance analysis should enable using TCO models to support both monitoring and planning tasks over the life cycle of the assets. Therefore, two approaches should be adopted within TCO: i) ex-post estimation, when TCO calculation is based on historical or actual data of the asset behaviours, in order to support monitoring tasks; ii) ex-ante estimation, when the TCO calculation is based on estimated future asset behaviours, in order to support planning decisions.

making that can support asset users in taking decisions along the asset lifecycle by integrating their knowledge about the asset performance within the model. In this way, the tool also allows managing data and information from asset providers, through a model that is grounded on the asset expected behaviour. More specifically, the methodology is based on an integrated modelling approach that puts together technical performance analysis and economic analysis. The technical performance analysis allows the estimation of the performances of the asset over its lifecycle; the economic analysis allows evaluating the cost items of a predefined Cost Breakdown Structure (CBS), by using as input both cost parameters and the outputs from the performance analysis. The integration of the two analysis finally allows calculating the TCO of the asset under study.

4.2. TCO building methodology phases and activities

The methodology for building the TCO model is hereafter described by detailing each activity that is required for it to be implemented. Different steps and procedures have been proposed in the literature for implementing a TCO analysis (Kumar et al. 2006; Barringer 2003; Kawauchi and Rausand 1999; Greene and Shaw 1990). Informed by them, the methodology organizes the required steps and procedures into three phases: (A) project setting; (B) performance analysis; (C) economic analysis. Each phase is then detailed in several activities as it is shown in Figure 1. Compared to previous approaches, a distinguishing feature of the methodology herein proposed is remarkable: the performance analysis of the asset is a necessary step towards TCO modelling and analysis, and a particular concern is given on the impacts of component assets behaviours, hence local performance losses, on the asset systemic performance, hence systemic performance losses.

(A) Project setting

The first phase of the methodology aims at setting the project's scope in terms of asset under study and asset-related decisions. Correspondingly, it defines the CBS applicable to the project's scope; moreover, the cost items in the CBS are categorized as deterministic and stochastic in view of the uncertainty of the asset behaviour, to properly establish the estimation methodology and required input data.

Step 1 – define asset under study and scope of asset-related decisions. The first step of any TCO analysis is a clear definition of the problems and the scope of analysis (Kawauchi and Rausand 1999). To do so, the asset (system or single equipment) to which the TCO analysis refers is first determined. The scope of asset-related decisions is then identified including the type of addressed decision-making process and the company's context. In fact, the TCO model may be used for supporting different asset-related decisions (as it was found in the literature and in the case study findings as well). Therefore, in this step, the decision-making process to be supported should be defined while selecting both the stakeholders of the analysis (asset user or provider) and the life cycle phase in which the asset is at the moment of the analysis (BOL, MOL or EOL). Moreover, at this step, clear assessment of the context in which the company operates (i.e. market, community, company's strategy, technology) is essential since it has remarkable impact on the requirements for asset management (EN 16646:2014 2014). The asset under study and scope of asset-related decisions impact on the TCO model to be developed. This step guides the definition of the Cost Breakdown Structure and the selection of cost estimation methodology in the following two steps, including relevant cost items for the specific application case.

Step 2 – define cost breakdown structure. It is important that all cost items that influence the TCO of the asset under analysis are considered in the model. Thus, it is normally recommended to define a CBS as a basis to the identification of the cost items in the TCO analysis. Indeed, the CBS represents the framework for identifying the life-cycle costs: it provides the communications link for cost reporting, analysis, and ultimate cost control (Fabrycky and Blanchard 1991).

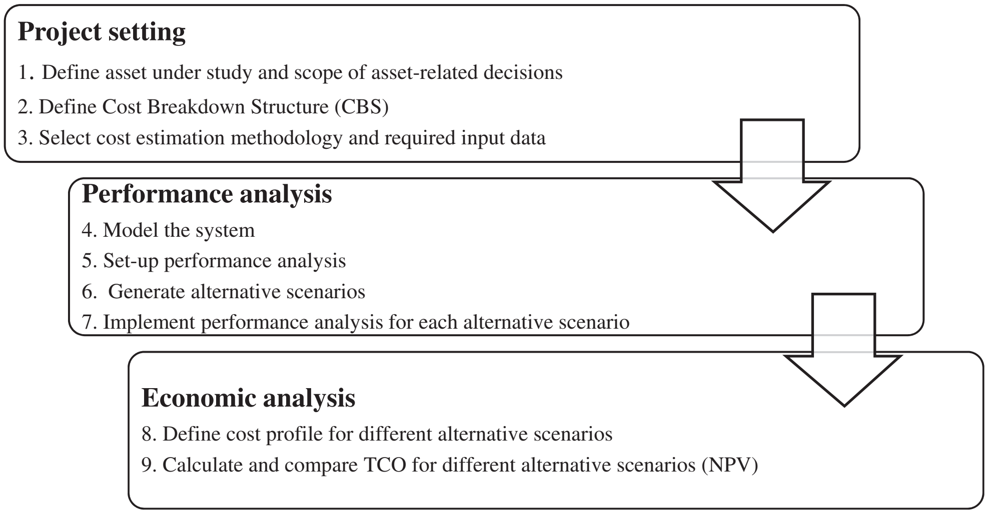

Figure 1. Outline of the TCO building methodology.

As stated by Kawauchi and Rausand (1999), it is difficult to identify the cost items that are applicable for every TCO analysis, because TCO may be applied to various scope of asset and kinds of decision. Nevertheless, some cost categories at the highest level can be identified that are commonly used in TCO analyses: they represent the first basis from which to detail specific CBS for specific application cases. The main cost items categorization approaches that can be found in the literature are illustrated in the reminder. Cost items categorization can be based on the organizational activities needed to bring a system 'into being' (Fabrycky and Blanchard 1991). In this case, the cost categories are defined based on the life cycle stage of the asset where the cost items fall in. For example, Fabrycky and Blanchard (1991) identified four main categories, each of it containing different cost items: (1) Research and development cost; (2) Production and construction cost, (3) Operation and support cost, (4) Retirement and disposal cost. Gram and Schroeder (2012) also considered a similar categorization for their investigation on the importance given by companies to each cost item under each category. Cost items categorization can also be based on the financial perspective. In this case, cost items are typically classified in two categories: Capital expenditure (CAPEX) and Operation expenditure (OPEX). In some cases, these categories are called with different names; for example, Barringer and Weber (1996) call them Acquisition costs and Sustaining costs while Chen and Keys (2009) defined them Ownership costs (referring to CAPEX) and Operation costs. In some cases, a separated category is added to CAPEX and OPEX that is related to the deferred production/losses due to inefficiencies (unavailability, etc.). It is the case, for example, of the (ISO 15663–2:2001 2001) that uses the following three categories: CAPEX, OPEX and Revenue impact (based on the production profile given in the plan for development and operation).

In spite of the different categorizations, in the end, the detailed costs items list will depend upon the particular asset and kind of decision under consideration (Asiedu and Gu 1998; Kawauchi and Rausand 1999). In this regard, two recommendations are worth to be remarked: i) the CBS should be designed so that the analyst can perform the necessary TCO analyses and trade-off assessments, in order to suit the objectives of the project and the company's concern in the specific project's scope (Woodward 1997); ii) the CBS should be simple and precise, in order to suit only the decision-making under study. Hence, if the decision requires to choose the best alternative from several ones, then only the cost items which really differentiate the alternatives should be considered (Kumar et al. 2006).

Step 3 – select cost estimation methodology and required input data. The cost items within the defined CBS can be classified into deterministic or stochastic cost items. In general, those cost items that are linked to system state and performance parameters are assumed to be stochastic, which expresses their relationship to the inherent uncertainty of the asset behaviours. Therefore, several cost items within the OPEX may be considered stochastic, due to their dependency on the asset performance parameters; examples are cost of energy, cost of maintenance and all those hidden costs like production losses costs due to unavailability, speed losses costs, non-quality costs (Parra and Crespo 2012; Thiede et al. 2012; Wudhikarn 2012). All other cost items are typically set deterministic, which means that the asset behaviour is assumed as known for the complete life cycle (Fleischer et al. 2007). Overall, only some of the cost items enlisted in the CBS are considered stochastic, depending on the project's scope: the analyst should define their categorization, either deterministic or stochastic, thus aligning with the objectives of the project and the company's concern. Once the cost items have been categorized, the estimation method for each of it must be defined and input data needed for the estimation should be identified.

(B) Performance analysis

The second phase of the methodology aims at building the performance models and properly quantifying the performance parameters required as input for the evaluation of the cost items in the CBS. Different alternative scenarios, due to the asset-related decisions as defined in the project's scope, are generated to be evaluated through technical performance analysis.

Step 4 – model the system. A critical aspect in the estimation of systems' performances is given by the complex structure characterizing the manufacturing assets themselves, that makes the modelling step hard to implement (Fowler and Rose 2004; Manno et al. 2012). Reliability Block Diagram (RBD) is proposed in this paper to cope with this modelling challenge. In fact, modelling a complex system by using RBD is a well-known method, adopted in order to make reliability and availability analysis. In particular, this method enables to represent the functional-logic connections among components of a system; this is useful, for example, to show how a failure in a plant component affects the whole process uptime in the entire plant (Birolini 2007; Keeter 2002; Macchi et al. 2012). A RBD model is built after a logical decomposition of a system into its subsystems up to the components level. Therefore, it has the advantage of giving an integrated view of the system while keeping an easy implementation approach built by means of a hierarchical modelling of the system under study (Macchi et al. 2012). Moreover, the RBD is drawn out to express, in a network of subsystems/components at each level of the hierarchy, reliability logics like series, parallel (total or partial redundancy), standby and, even, multi-state systems (MSS) enabling to model working states corresponding to different performance rates (i.e. different performance decays). By means of these logics, the manufacturing asset can be modelled and its performance analysed. The components/subsystems are combined in order to model the entire asset system, and to analyse the effects of a failure or a performance decay occurring in a subsystem (e.g. a subset of machines), both as local – within the scope of the subsystem – and global effect – within the scope of the whole system. RBD modelling can be implemented in industrial practice as it is supported by software (see

Availability Workbench^{TM} by ARMS reliability; Relex, BlockSim by Reliasoft or R-MES Project© by CGS as examples of software products on the market).

For all the above reasons, the methodology proposed in this paper adopts RBD as method to support modelling and technical performance analysis of manufacturing assets. In particular, at the present step of the methodology, RBD model is used in order to represent the functional-logic connections that exist among components/subsystems of a whole system. Afterwards (at the next step 5), the RBD model will be the basis to make the quantitative assessment of the properties of the system, such as its reliability and availability, or the downtimes that can be expected at the system or at the subsystem level, or the throughput.

Step 5 – set up performance analysis. This step includes two main activities: (i) definition and set-up of the quantification method for the performance parameters, (ii) identification and collection of the required data.

Based on the requirements previously described (Table 8), and considering the aim of TCO evaluation, both ex-ante and ex-post estimation can be considered.

Quantification methods adopting an ex-ante estimation are the most proper ones in order to be able to predict the costs along the lifecycle of an asset by estimating its future performance. In the methodology proposed in this paper, the use of stochastic simulation is considered to this end. In particular, the Monte Carlo next-event simulation (Rausand and Høyland 2004) is adopted in conjunction with the RBD method. The simulation approach allows generating random events occurrence by relying on the probability distribution functions of, e.g., time between failures and time to repair of each component in the system (that are given in input). Hence, the time at which an event occurs and the duration of the event are determined by generating random numbers, in accordance with the Monte Carlo method. The failure and end repair times are then two events traced out at each equipment/component of the system during every simulation run. Once the set simulation period expires, the calculation of availability and throughput of the asset system, e.g. the production line, is straightforward, thanks to the RBD model (Macchi et al. 2012). The performance losses related to the failures and repairs are assessed for their effects (impacts) on the systems' performance, by means of a bottom-up approach that passes through the RBD logics expressed along the hierarchical model of the asset system. The final result is a statistical estimate value of operational availability and throughput (or other performances) of the complete asset system, and of any of its sub-systems, that can be used as input for the calculation of the hidden costs related to systemic performance.

Quantification methods adopting ex-post estimation are the most proper ones in order to be able to measure and, then, monitor the costs along the lifecycle of an asset by estimating its historical and actual performance. Similar to ex-ante estimation, also in this case RBD is used in order to convert measures of local effects – at component/subsystem level – to global effects – at system level. The difference, now, is that the actual events (not the simulated ones) are traced out at each equipment/asset of the system during every monitoring period and, then, are used to calculate, through the RBD model, the operational availability (or other performances) of the complete asset system.

In both the two cases, the necessary data for the performance evaluation of the system under analysis concern the elementary components (i.e. asset component) of the system itself at the lowest aggregation level included in the hierarchy of the RBD model. At this level, historical data can be collected during a monitoring period. When a prediction is required, the monitored data can be adopted to define (through appropriate data fitting algorithms) the probability distributions to be used by the Monte Carlo simulation. Other approaches can be adopted as well, as alternatives for prediction: (i) if historical data of the asset under study are lacking, the use of experts' estimations and predefined distributions, such as the triangular distribution, is a viable option; (ii) if benchmarking historical data relating to similar assets operating in similar conditions are available, they may be analyzed in order to define the probability distributions (through data fitting algorithms) to be used, based on similarities, for the asset under study. The above possibilities are not mutually exclusive but can be combined in function of the availability of the data from each source.

Overall, once the RBD model of the system is defined (at previous step 4), and technical data have been collected for each component asset, calculation through monitored or simulation runs, can be performed. When using simulation, the following information must be previously set: (i) the number of simulation runs (that is, number of simulated life cycles of the asset) to be carried out; (ii) the simulation period (that is, the lifetime under study), which therefore coincides with the duration of each simulation run.

Step 6 – generate alternative scenarios. This step is needed to define which are the alternative scenarios to be evaluated through the performance-driven TCO, and it is based on asset-related decisions as defined in the project's scope (i.e. at step 1). The generation of alternative scenarios to be evaluated through TCO can regard both asset configuration and asset operations management solutions.

Step 7 – implement performance analysis for each alternative scenario. Once the alternative scenarios are defined, the technical performance analysis is implemented for each of them in order to be able to estimate the improvement it can bring with respect to the as-is scenario (i.e. base case) and to calculate, in the following steps (steps 8 and 9), the corresponding differential TCO (i.e. differential with respect to the base case).

In case the project's scope refers to existing assets improvement decisions, i.e. brownfield project, first of all, the as-is scenario is modelled according to the current installation, and the performance analysis is run in order to have a reference indication about current performance and TCO. After that, the changes that each scenario implies must be brought within the RBD model by accordingly changing the as-is model. For example, in case the alternative scenario deals with asset configuration changes like the installation of a new equipment, the as-is model must be changed by adding the new component assets in the model as new blocks with their corresponding technical data. The new model and data can then be used to implement the performance analysis by simulating the asset behaviour if the alternative scenario would be implemented. These activities have to be done for each alternative scenario to be evaluated. The output of this step is the calculation of the estimated life cycle performance of each alternative scenario, that can be compared with the as-is scenario's performance.

Alternatively, if the project refers to a new asset, i.e. greenfield project, modelling and simulation are useful tools to estimate expected performances of alternative scenarios in terms of configuration and/or managerial solutions, with a similar approach as brownfield, i.e. performance improvements with respect to a base case, to subsequently calculate differential TCOs (i.e. at next steps 8 and 9).

(C) Economic analysis

The third and last phase of the methodology aims at developing and computing the cost profiles required for different alternative scenarios under study in the decision-making process. Using the discounted cash flows, all the cost items are actualized in order to obtain the TCO as present value.

Step 8 – define cost profile for different alternative scenarios. The cost profile for each alternative scenario under analysis is defined by the quantification of the cost items that occurs along the life cycle. It basically corresponds to the quantification of the cost items as defined in the CBS, and their distribution along the life cycle of the asset.

Step 9 – calculate and compare TCO for different alternative scenarios. Since the development of cost profiles includes cash flows that will occur in the future, all cost items must be actualized to a common time base for calculating a TCO value that can be used to take decisions. Discounting takes care the fact that money has time value and calculates all costs to the present value for easy comparison. The discounted cash flows calculation is adopted; in particular, TCO is calculated as the discounted sum of all cost items affecting an asset along its life cycle (Gram and Schroeder 2012). The final aim is the evaluation and comparison of the generated alternatives based on the value of the TCO obtained for each scenario.

5. Application case study

The methodology for building the performance-driven TCO model has been applied in a field case within a large chemical company competing at international level. The focus is one of the plants of the company, in particular, one of its rubber production lines. The line produces Styrene-Butadiene-Styrene copolymers to be used in bitumen modification for plastic modification and footwear. The plant was installed in the 80ies and undertook some revamping during its life.

The main objective of the case is to apply the methodology to build a performance-driven TCO model, with the final aim to validate its potentialities for supporting asset-related decision-making. The methodology is applied by the user's perspective (owner and manager of the plant) dealing with the Middle of Life (MOL) stage of its assets. 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 and new acquisition investments while a close linkage of the asset performance, influenced by the technical changes, and costs, is deemed essential for proper TCO prediction.

The project was developed with the collaboration of the maintenance and technical material executives of the company, and the maintenance function personnel and the technology function personnel of the plant. To ease application, a software-based tool for asset management using Monte Carlo simulation was adopted, i.e. R-MES Project© by CGS (www.cgssa.com). The construction of the cost profile was obtained manually, through spreadsheets built by importing and re-organizing the data produced by R-MES project. The next sub-sections illustrate each step of the proposed methodology in the case study.

5.1. TCO building methodology in the application case study

(A) Project setting

Step 1 – define asset under study and define scope of asset-related decisions. The asset system to which the TCO analysis refers is the finishing section of the production line of one of the biggest plants owned and managed by the company. The finishing section is the process downstream the chemical processing. The crumb slurry, previously processed, is pumped to the finishing section, where it is dewatered mainly through a mechanical process. The polymer is then cooled with air, and prepared (weighed and baled) to be stocked. The main context's characteristics to be considered are the followings:

- the plant operates with a continuous flow 24/24 and every 18 months a general overhaul (lasting around 1 month) is planned;
- the plant produces different kinds of products by using quick set-ups;
- the market is characterized by unsaturated demand (hence, if availability is increased then this can be turned into profit).

The type of addressed decision-making process were then identified: reconfiguration decisions/new acquisition investments, implying a partial re-design of the plant structure.

Step 2 – define cost breakdown structure. At this step, the cost items to be included in the CBS were identified considering that the intended analysis is a differential TCO analysis. In fact, after assessing the as-is situation's TCO, the company wanted to evaluate the changes in the technical performances and costs by the implementation of re-design solutions. For this reason, it was sufficient, for the purpose of the specific analysis, to refer to only those cost items reflecting a variation in the design scenarios compared to the as-is case. Based on these considerations, the cost items that were selected for the CBS are enlisted in Table 9: the cost items were first categorized as CAPEX and OPEX, according to the financial perspective and, afterwards, considering the life cycle stage, i.e. BOL, MOL, EOL. Specifically, the hidden costs related to performance losses (to unavailability) were categorized within the OPEX.

Step 3 – select cost estimation methodology and required input data. The cost items within the defined CBS were classified as deterministic or stochastic cost items. As a result, corrective maintenance losses related cost, under the hidden cost category, is the only stochastic item, and it depends on the estimated availability of the assets along the life cycle, as stochastic performance; instead, the other cost items are considered deterministic in the project's scope. Correspondingly, the estimation formulas are also defined: Table 9 provides the input data needed for the estimation and the output of cost calculation (when cost calculation is the case, otherwise the output is coincident with the input).

(B) Performance analysis

Step 4 – model the system. The modelling phase was based on two main objectives:

1. the identification of the main equipment which compose the finishing section of the line under analysis; the aim was to define the equipment-list of items to be encompassed in the RBD model of the industrial plant, including sub-components and failure modes of such equipment;
2. the identification of the effects (impacts) of the failures of each identified component/failure mode on the system capacity, in order to be able to combine them through the proper RBD logics to finally express how the finishing section of the line can work, eventually at degraded performance.

First, to perform a functional analysis of the finishing section of the line and to meet the first modelling objective, a tree structure of the line itself was developed. The aim was to facilitate the identification of the main equipment (level 1 of the tree), to be included in the equipment-list, and of their subcomponents. The Process Flow Diagram (PFD) of the line was the reference for a visualization of the equipment and the understanding of the process. Through a conjunct work with the maintenance personnel and the technology personnel, the following three hierarchical levels were identified composing the finishing section.

- Level 1: the main equipment, that is, those that correspond to a functional location of the asset system (i.e. the finishing section of the line) in the ERP system.
- Level 2: the sub-components of the items identified in the previous level. Each sub-component can lead to one or more failure modes of the equipment. The failure modes have been identified in two ways: on one side, a corporate archive containing data and information on failure modes for many of the equipment of the first level in the tree was used; on the other side, the historical database of work orders for maintenance was used, from which, by reading the text describing the orders, it was possible to understand to which specific subcomponent failures on the first level item were due.
- Level 3: a further explosion of the identified items at the second level was necessary only if the failures of an item

Table 9. Defined CBS in the application case – cost items and estimation methods.

Cost item	Estimation method	
	CAPEX	
Beginning of Life costs		
Investment cost	INPUT: Purchasing price of new solution [euro]	OUTPUT: Purchasing price of new solution [euro]
Installation fixed cost	INPUT: Fixed Installation cost of new solution [euro]	OUTPUT: Fixed Installation cost of new solution [euro]
Installation labour cost	INPUT: Man hours to install [hours]; Installation hourly labour cost [euro/hours]	OUTPUT: Installation labour cost = Man-hours to install * Installation hourly labour cost [euro]
	OPEX	
Middle of life costs		
Maintenance labour cost	INPUT: Maintenance hourly cost [euro/hour]; N_{CB} = Number of operators for maintenance activities in the as-is case; N_{Si} = Expected number of operators for maintenance activities in the i-th scenario; Yearly opening hours [hours/year]	OUTPUT: Maintenance Labour cost = Maintenance hourly cost * (N_{Si} – N_{CB}) * Yearly opening hours [euro/year]
Energy cost	INPUT: E_{CB} = Yearly energy consumption in the as-is case [kwh/year]; E_{Si} = Expected yearly energy consumption in the i-th scenario [kwh/year]; Electric Energy cost [euro/kwh]	OUTPUT: Energy Cost = Electric energy cost * (E_{Si} – E_{CB}) [euro/year]
Corrective maintenance losses related cost (hidden cost)	INPUT: MC = contribution margin [€/unit]; A_{CB} = A resulted in the as-is case [%]; A_{Si} = expected A for the i-th scenario [%]; CP = nominal capacity [units/year]	OUTPUT: Corrective maintenance losses related cost = MC * (A_{Si} – A_{CB}) * CP
End of life costs		
Disposal cost	INPUT: Decommissioning cost at EOL year of new solution [euro/year]	OUTPUT: Decommissioning cost at EOL year of old solution [euro/year]

of level 2 are attributable to a broad set of its subcomponents/failure modes.

On the whole, Table 10 summarizes the number of items at each hierarchical level. It is worth remarking that the 74% (32 over 43) of the equipment at level 1 are functional equipment for the production process while the 26% are utilities service equipment.

Based on the items identified so far at different levels, it was then possible to better define the contribution by each equipment, as well as by its sub-components, to the performance of the entire line in terms of availability. Indeed, the second modelling objective was the definition of the reference model of the finishing section of the line, made by means of a functional-logic perspective that combines the equipment and the sub-components through the RBD method. The diagramming was built in two stages.

At first, a pilot model was developed based on the analysis of the PFD, and supported by the information provided by the experts of maintenance and process technology. Experts were important to get information regarding the effect (impact) on the nominal capacity in case of failure/stoppage of each of the item to be included in the model of the system, until the lowest level of logical decomposition decided for the model (i.e. items at either level 1, 2 or 3). This information provides guidance on any redundancy, standby system and MSS logic to be expressed in the RBD model, and on the impact factor of the items on the availability and, then, on the system capacity, which finally allows to define the correspondent performance loss at the system level (i.e. in the range from no loss to total loss). Afterwards, a closer collaboration was needed with the field experts for some clarification on the operation and the impact of a failure to the process with regard of the components of some sections of the line. In particular, information about the potential performance decays that could happen to the equipment in the system as well as their impact on production continuity or product quality required talking with the experts to complete the modelling stage.

Table 10. Number of items at each level modelled in the RBD.

Level	# Items
1	43
2	86
3	39

Figure 2 shows an excerpt of the functional-logic modelling performed with the support of the software R-MES. It is possible to notice, in the image, a tree structure of the finishing section of the line on the left that considers the RBD logics according through which the different items of the model are functionally linked. A graphical representation of the RBD model as composed by building blocks is visualized on the right, as each block represents a part of the finishing section of the line and can be exploded in its sub-components until the lowest item level decided for the system model.

Step 5 – set-up performance analysis. Given the objectives and scope of the project, an ex-ante estimation was the most proper approach to predict the costs along the lifecycle of the finishing section of the line by estimating its future performance. Stochastic simulation – supported by RMES – was used to this end.

In order to choose the best strategy for the required technical data collection, a previous analysis of the current status and availability of historical data was developed, considering that the line was already installed. In fact, the ideal condition is to use historical data in order to generate (by using data fitting algorithms) the probability density functions of the frequency and duration of failure events and repair times for each item in the model.

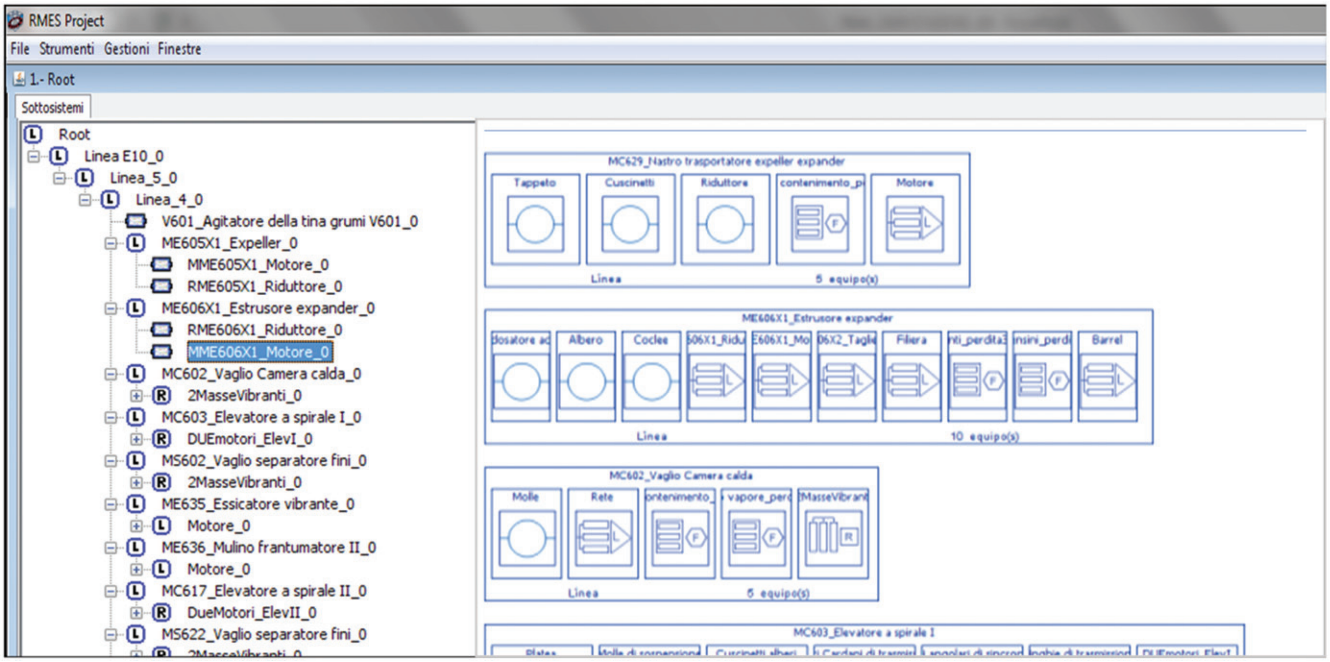

Figure 2. Extract of the schematic RBD diagram, visualized in RMES.

To address the data collection in an exhaustive manner, different types of sources had to be analyzed (among which, ERP Work orders list, production losses registers, annual orders, work orders long texts, daily reports, etc.). The performed analysis of the data aimed at understanding whether they were enough in order to derive a probability density function of time between failures (TBF) and time to repair (TTR) parameters for each of the items in the model. By analyzing the data availability, the items (equipment and sub-components) could be categorized under two situations: both i) equipment/sub-components with historical records but not enough in number and ii) equipment/sub-components with no historical records. Due to this evidence, the use of historical data base and fitting was considered as a weak strategy for the specific project's scope. To overcome this limitation, it was decided to rely on field experts' judgment as the method for estimating TBF and TTR, given the peculiarities of the plant that made it not possible to look for benchmarking historical data.

For each component/failure mode, in relation to items at the lowest level of decomposition that was decided for the plant modelling, maintenance and technology experts were asked to estimate values of TBF (frequency of occurrence: minimum, maximum and mode) and values of TTR (time to recover to operation: minimum, maximum and mode). In fact, the traditional solution of using triangular distributions in case historical data are missing was adopted for defining the probability distributions that are needed as input for the simulation (Clarke 1990). The data collection process resulted quite articulated since the opinions of maintenance personnel and technology personnel were required for each item in the model. In particular, the maintenance personnel provided the input data for 156 items and the technology personnel for 6 items. Finally, a complete database was available and could be used as input for the performance analysis.

Step 6 – generate alternative scenarios. Three variants scenarios, with respect to the as-is case of the finishing section of the line, were defined as the alternative scenarios to be evaluated. They were defined by taking into account a criticality analysis on the current performance of the system and its various components and on experts' advice, who expressed particular interest in testing some specific solutions (the expert's advice was needed to integrate a proper knowledge on the technical feasibility of the solutions).

The generated alternatives are the followings:

- **Scenario A:** installation of a new extruding machine, to be kept in stand-by with the already existing one;
- **Scenario B:** disposal of the existing transporter and its substitution with a new technological solution;
- **Scenario C:** installation of three more screens in redundancy to the existing ones.

The three scenarios are aligned with the asset-related decisions as defined in the project's scope, as they lead to asset reconfigurations and new acquisition investments to be decided.

Step 7 – implement performance analysis for each alternative scenario. As a first step, the Monte Carlo simulation was run for the as-is scenario: 200 simulation runs (which resulted the best number of runs looking at the trade-off among accuracy of results and time for simulating) were conducted to calculate the desired KPIs (system's availability). The output of the Monte Carlo simulation is the probability distribution of the systemic availability of the line under analysis. The median value (i.e. the value with 50% probability to be reached or overcome) was taken as the reference estimation of the output value as defined in agreement with the company.

After evaluating the performance for the as-is situation, the corresponding performance analysis was developed for each of the three identified alternative scenarios, allowing estimating the performance changes related to each of it. More in detail, for each alternative scenario, the RBD model was changed depending on the modifications that each case implied, and new input data were fed for the new item(s) included in the model. Given the model reflecting the alternative solution, the simulation was run, and the systemic performance of each scenario was obtained as output. It is worth remarking that the time to change the model was very short, in fact, it was a matter of adding/removing blocks from the defined as-is RBD model. This is one of the potentialities of the approach that was most valued by the company.

The first scenario (scenario A) implies the installation of a redundancy in the line, addressing the most critical equipment which resulted to be one of the two extruding machines. In order to estimate the performances of the new scenario, the first step that was implemented was the modification of the reference RBD model (as-is) by inserting a new block representing the new equipment that was interconnected to the existing extruding machine block through a stand-by logic according to the defined scenario. As far as the technical input data for the new equipment regards, the agreed solution was to build triangular distributions for TBF and TTR probability distribution functions by using the characteristic parameters of the old equipment and improving them. In fact, no meaningful benchmark equipment could be identified apart from the existing one. Based on the defined modified model, simulation was run, and the following systemic availability was estimated in case scenario A solution was implemented.

The second scenario (scenario B) addresses one of the two existing transporters and supposes its substitution with a new technology (pneumatic transport system). As it was done for the previous scenario after the as-is RBD model was modified according to the scenario (i.e. replacement of a vibration transporter with a block representing the new transport system) and the data for the new item were inserted, simulation was run.

The third scenario (scenario C) refers to the existing screens in the line and supposes the installation of new screens in stand-by to the existing ones. The same steps as for scenario A were followed and the performance analysis was implemented for scenario C.

Overall, the technical outputs in terms of systemic availability for each scenario were evaluated with respect to the as-is scenario (see Table 11). These, as performance

Table 11. Performance analysis of each alternative scenario (differential with respect to the as-is case).

Scenarios	Description	Δ A *with respect to the as-is case*
SCENARIO A	Installation of a new extruding machine, to be kept in stand-by with the already existing one	+9.42%
SCENARIO B	Disposal of the existing transporter and its substitution with a new technology	+2,33%
SCENARIO C	Installation of three more screens in redundancy to the existing ones	+3,98%

parameters, are used in the next step, combining with the related cost parameters, to make the economic evaluation.

(C) Economic analysis

Step 8 – define cost profile for different alternative scenarios. To define the cost profiles of each of the alternative scenario, the differential costs and cost savings with respect to the as-is situation were considered for each case – energy consumption, acquisition and installation costs, end of life disposal costs, … –, as well as the additional margin resulting from the increase in availability and, then, from the higher production volume sellable to the market. In practice, the estimation formulas expressed in Table 9 are now fulfilled with the performance and cost parameters for all the scenarios.

Step 9 – calculate and compare TCO for different alternative scenarios. The objective of this step was to calculate, in a differential way, the ΔTCO, to evaluate how the costs would vary along the life cycle of the finishing section of the line if the proposed technical changes by the scenarios under consideration were implemented. The indicator assumes the following form:

$$\Delta TCO_i = TCO_{Scenario_i} - \ TCO_{As-is\ \ case} \tag{1}$$

Getting a negative ΔTCO would, then, mean that the costs that characterize the life cycle of the finishing section of the line under study would be lower than in the as-is situation. More specifically, after establishing a lifetime period for the evaluation of the various scenarios, the cost model allows estimating the differential money cash-flow over the asset lifecycle for each scenario with respect to the as-is case. Once the ΔTCO was calculated for each scenario with respect to the as-is case, the company could compare the different solutions. Solution A resulted to be the most convenient among the three: even if it required a higher initial investment cost (thus, higher CAPEX) than the others, and resulted in a slightly higher payback time (any way, lower than three years), it was the one ensuring the lowest TCO considering the long term perspective and hence ensuring higher future cost savings.

5.2. Concluding remarks

Considering the experience within the company case, it can be concluded that the TCO model building methodology allows to exploit the potentialities of TCO adoption to support asset-related decision-making. Additional insights, both to confirm and to extend previous findings, were raised by the case.

When implementing the performance analysis for each scenario, the company's personnel confirmed the issue of possible low quality of data from asset providers. Nevertheless, the application motivated the need to foster collaboration between asset users and asset providers for a successful use of a shared TCO model. With this specific regard, in fact, the company's personnel remarked that the TCO model developed so far appeared to be an interesting tool to strengthen as well as to govern the relationship with the asset providers/suppliers. In particular, the performance model built in the TCO model was seen as a kind of mechanism to enable the different actors involved in the plant (i.e. with an asset-centric approach) to share knowledge, on the asset configuration and utilization, from the user's perspective, and on the asset expected behaviour from the provider's perspective. Therefore, based on such an objective tool, that can lead them both to take beneficial decisions, communication and collaboration could be supported. In the company's perception, this is expected to be mostly beneficial during the BOL stage of an asset, primarily to drive the purchasing contract specifications while keeping a long-term perspective when taking asset-related decisions through an indicator, the TCO, that is built and shared among the asset user and provider(s).

As far as the implementation and use concern, in the perception of company's personnel, the adoption of RAM modelling techniques (i.e. namely the RBD technique, with hierarchical modelling of the system), combined with the Monte Carlo simulation, appeared to be a quick engineering way in order to evaluate trade-offs among availability and redundancy, thus to have a system-level analysis of performance losses. Furthermore, according to their feedbacks, it resulted that performance analysis and, specifically, reliability engineering are fundamentals for financial and economic evaluations referring to capital-intensive and complex asset systems. Eventually, the methodology was also judged as a method with good potential to drive, in a standard way, the TCO model building and use.

From a cultural point of view, the company could be considered advanced in the maturity to introduce the TCO analysis. Thus, it may be asserted that there was an indirect confirmation of the importance to prepare the cultural background, having the involved personnel approaching the decision-making process with a long-term perspective. Overall, after the case was developed and the results generated, the plant management confirmed the usefulness of the model as a tool for supporting the investment decisions by proving, with a sound engineering approach, the return of an investment taking into account the life of the asset and its performance along it, going beyond the pure acquisition cost.

On the whole, the performance-driven TCO model that results from the proposed methodology and its application in the company case presents as main limitation the fact that stochastic cost parameters are not considered. This issue opens perspectives for future work to extend the methodology.

6. Conclusions

The research presented in this paper aims at renovating the investigation on TCO in order to discover new understanding and needs in industry and, subsequently, new requirements for scientific research. The focus was put on the potentialities of TCO as a tool for asset users to support asset lifecycle management. The main findings, obtained through literature analysis and multiple case study involving eight manufacturing companies, allowed discovering new perspectives and the main existing challenges for TCO application.

In fact, even if TCO is traditionally considered and used as a purchasing tool supporting products/systems users in the vendors selection process, the current trend in industry is to look at it as a tool that can support the decision-making along the whole lifecycle of assets, enabling long-term perspective. This finding was identified in the literature and confirmed by the multiple case study, with specific concern about the manufacturing sector.

For TCO to become a useful tool for supporting asset management decision-making, the need of grounding it on performance analysis emerged as a crucial issue. More in detail, three main aspects arose: i) the need to integrate cost evaluation with technical analysis of the expected behaviour of the asset along its lifecycle considering uncertainties related to failures and performance decays, ii) the need for the technical analysis to quantify performance losses at system level, and iii) the need to implement technical analysis both through an ex-ante and ex-post approach, in order to use the TCO both as a planning and monitoring tool, depending on the lifecycle stage at which it is used to support decision-making.

The proposed methodology to build a TCO model aims at addressing these requirements and is composed of three main phases: project setting, performance analysis and economic analysis. It allows combining the reliability engineering concept with the economic and financial evaluations, which is essential to strengthen the connection between technical asset management and profitability.

Its application in the industrial case let emerge the novelty of the approach in which the technical performance analysis based on the asset system model become the central point along which knowledge about the asset can be collected and integrated. In fact, through the performance model, the asset user ensures an asset-centric perspective through an objective model that can also be used to communicate and collaborate with the asset providers.

In this way, TCO becomes a strategic tool to support asset-related decision-making, enabling centralizing and keeping track of data and information of different kinds (technical and economic) that characterize the manufacturing assets managed by a company. In fact, it is promising to avoid the typical silos approach when different functions involved with the asset at different stages of its lifecycle (purchasing, production, maintenance, energy, etc.) take decision by looking at the data under their ownership and their specific objectives. The use of a tool, like the TCO, enables ensuring that decisions are taken with one objective that is the profitability along the asset lifecycle, collecting data from different functions and systems all together through an asset-centric approach.

A main challenge that remains for industrial applicability is the need for organizational culture and leadership that commit towards long-term oriented decision-making and integration among functions in a multi-disciplinary approach. It will be then interesting studying how asset management principles could become a background in company's organizations to foster such a long-term perspective and multi-disciplinary approach, as pre-requisites for the achievement of a systematic implementation and use of TCO for decision-making.

Another challenge, and interesting focus for future research, regards the adoption of an integrated management that joins planning and monitoring over different lifecycle stages, from BOL to EOL. It will be interesting to investigate the use of such an approach, built by combining different capabilities such as modelling and simulation, systematic tracking of changes and performance monitoring, to finally lead to a decision-making support that is asset-centric and fully integrated along the asset life.

Acknowledgements

This paper originates from the research path that we shared with our mentor the late Professor Marco Garetti and is presented in his memory.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Irene Roda is Assistant Professor at the Department of Management, Economics and Industrial Engineering at the Politecnico di Milano. She has a PhD in Industrial Engineering, specializing on physical asset management. She is co-director of the Observatory on Technologies and Services for Maintenance of the School of Management of Politecnico di Milano. She is Teaching Assistant in the MSc course on Asset Lifecycle Management. She is lecturer in the Executive Master in Maintenance and Industrial Asset Management (meGMI) and in the International Master in Industrial Management at the MIP Politecnico di Milano Graduate School of Business. Her research interests are in industrial engineering, with special concern to asset management and operations and maintenance management.

Marco Macchi is currently Full Professor at Department of Management, Economics and Industrial Engineering of Politecnico di Milano. His teaching and research regard industrial technologies, asset lifecycle management, operations and maintenance management. Serving the scientific community, he is currently Vice-chair of the IFAC TC 5.1 Manufacturing Plant Control, and Chair of the IFAC Working Group A-MEST (Advanced Maintenance Engineering, Services and Technology), WG affiliated to the IFAC TC 5.1; he is Member of the IFIP WG 5.7 Advances in Production Management Systems and the IFAC TC 5.3 Enterprise Integration and Networking; besides, he is Book Reviews Editor and Editorial Board Member of the International Journal Production Planning & Control: The Management of Operations, Taylor & Francis.

Saverio Albanese is Maintenance and Technical materials Executive at Versalis SpA. Versalis is the Eni S.p.A chemical company, leading the market in a host of businesses such as plastics and rubbers. Since July 2016, he is President of the Italian Maintenance Society (A.I.MAN.) and he is Chair of the UNI (Italian National Unification body) Maintenance Commission.

ORCID

Irene Roda http://orcid.org/0000-0001-7795-1611
Marco Macchi http://orcid.org/0000-0003-3078-6051

References

Aberdeen Group. 2012. "Asset Management: Building the Business Case for the Executive". December. http://www.aberdeen.com/Aberdeen-Library/7937/RA-enterprise-asset-management.aspx.

Al-Hajj, A., and G. Aouad. 1999. "The Development of an Integrated Life Cycle Costing Model Using Object Oriented and VR Technologies." Proc., Information Technology in Construction: CIB W78 Workshop Durability of Building Materials and Components.

APPA 1000-1. 2018. "Total Cost of Ownership for Facilities Asset Management (TCO) – Part 1: Key Principles."

Asiedu, Y., and P. Gu. 1998. "Product Life Cycle Cost Analysis: State of the Art Review." *International Journal of Production Research* 36(4): 883–908. doi:10.1080/002075498193444.

ASTM E917 – 17. 2017. "Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems."

Barringer, H. P. 2003. "A Life Cycle Cost Summary." Conference of Maintenance Societies (ICOMS®-2003), 1–10.

Barringer, H. P., and D. P. Weber. 1996. "Life Cycle Cost Tutorial." Fifth International Conference on Process Plant Reliability, 1–58. Houston, Texas.

Birolini, A. 2007. *Reliability Engineering*. Berlin: Springer.

Bonetti, S., M. Perona, and N. Saccani. 2016. "Total Cost of Ownership for Product-Service System: Application of a Prototypal Model to Aluminum Melting Furnaces." *Procedia CIRP* 47: 60–65. Elsevier. doi:10.1016/j.procir.2016.03.069.

Bouachera, T., M. Kishk, and L. Power, 2007. "Towards a Generic Framework for Whole Life Costing in the Oil Industry." Proc. 23rd Annual ARCOM Conference, 863–871.

Boussabaine, A., and R. Kirkham. 2008. *Whole Life-Cycle Costing: Risk and Risk Responses*. Hoboken: John Wiley & Sons.

Bryman, A. 2009. "Integrating Quantitative and Qualitative Research: How Is It Done?" *Qualitative Research* 6(1): 97–113. doi:10.1177/1468794106058877.

Caniato, F., S. Ronchi, D. Luzzini, and O. Brivio. 2014. "Total Cost of Ownership along the Supply Chain: A Model Applied to the Tinting Industry." *Production Planning & Control* 26(6): 427–437. doi:10.1080/09537287.2014.918285.

Carpentieri, M., and M. Papariello. 2006. "A Life Cycle Cost Framework for Automotive Production Lines." In 3th CIRP International Conference on LCE, 711–716.

Carrubba, E. R. 1992. "Integrating Life-Cycle Cost and Cost-of-Ownership in the Commercial Sector." Reliability and Maintainability Symposium, 101–108.

Chen, S., and L. K. Keys. 2009. "A Cost Analysis Model for Heavy Equipment." *Computers and Industrial Engineering* 56(4): 1276–1288. doi:10.1016/j.cie.2008.07.015.

Clarke, J. D. 1990. *Life Cycle Cost: An Examination of Its Application in the United States, and Potential for Use in the Australian Defense Forces*. Monterey, California: Naval Postgraduate School.

Corbin, J., and A. Strauss. 2014. *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*. Thousand Oaks, CA: Sage Publications.

Datta, P. P., and R. Roy. 2010. "Cost Modelling Techniques for Availability Type Service Support Contracts: A Literature Review and Empirical Study." *CIRP Journal of Manufacturing Science and Technology* 3(2): 142–157. doi:10.1016/j.cirpj.2010.07.003.

El-Akruti, K., R. Dwight, T. Zhang, and M. Al-Marsumi. 2015. "The Role of Life Cycle Cost in Engineering Asset Management." In *Engineering Asset Management-Systems, Professional Practices and Certification*, edited by Peter W. Tse, Joseph Mathew, King Wong, Rocky Lam, C.N. Ko 173–188. Switzerland: Springer International Publishing.

El-Akruti, K., R. Dwight, and T. Zhang. 2013. "The Strategic Role of Engineering Asset Management." *International Journal of Production Economics* 146(1): 227–239. doi:10.1016/j.ijpe.2013.07.002.

Ellram, L. M. 1995. "Total Cost of Ownership: An Analysis Approach for Purchasing." *International Journal of Physical Distribution & Logistics Management* 25(8): 4–23. doi:10.1108/09600039510099928.

Ellram, L. M., and S. P. Siferd. 1998. "Total Cost of Ownership: A Key Concept in Strategic Cost Management Decisions." *Journal of Business Logistics* 19: 55–84.

Emblemsvåg, J. 2003. *Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks*. New York: John Wiley & Sons.

EN 16646:2014. 2014. "Maintenance – Maintenance within Physical Asset Management."

Enparantza, R., O. Revilla, A. Azkarate, and J. Zendoia. 2006. "A Life Cycle Cost Calculation and Management System for Machine Tools." 13th CIRP International Conference on Life Cycle Engineering, July 2015, 717–722.

Fabrycky, W. J., and B. S. Blanchard, eds. 1991. *Life-Cycle Cost and Economic Analysis*. Englewood Cliffs, NJ: Prentice Hall.

Ferrin, B. G., and R. E. Plank. 2002. "Total Cost of Ownership Models: An Exploratory Study." *Journal of Supply Chain Management* 38(2): 18–29. doi:10.1111/j.1745-493X.2002.tb00132.x

Fleischer, J., M. Wawerla, and S. Niggeschmidt. 2007. "Machine Life Cycle Cost Estimation via Monte-Carlo Simulation." In Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses, edited by S. Takata, Y. Umeda, 449–453. London: Springer.

Fowler, J. W., and O. Rose. 2004. "Grand Challenges in Modeling and Simulation of Complex Manufacturing Systems." *Simulation* 80(9): 469–476. doi:10.1177/0037549704044324.

Gram, M., and W. Schroeder. 2012. "Evaluating the Life Cycle Costs of Plant Assets: A Multidimensional View." *Serbian Journal of Management* 7(2): 287–298. doi:10.5937/sjm7-2545.

Greene, L. E., and B. L. Shaw. 1990. "The Steps for Successful Life Cycle Cost Analysis." IEEE Conference on Aerospace and Electronics, doi:10.1109/NAECON.1990.112942.

Gungor, Z. E., and S. Evans. 2017. "Understanding the Hidden Cost and Identifying the Root Causes of Changeover Impacts." *Journal of Cleaner Production* 167: 1138–1147. doi:10.1016/j.jclepro.2017.08.055.

Heilala, J., K. Helin, and J. Montonen. 2006. "Total Cost of Ownership Analysis for Modular Final Assembly Systems." *International Journal of Production Research* 44(18–19): 3967–3988. doi:10.1080/00207540600806448.

Hwang, H. S., S. T. Bae, and G. S. Cho. 2007. "Performance Model for Manufacturing Facility Planning Based on System Configuration, RAM and LCC." *International Journal of Innovative Computing, Information and Control* 3(1): 199–209.

IEC 60300-3-3. 2017. "Dependability management - Part 3-3: Application guide - Life Cycle Costing."

ISO 55000:2014. 2014. "Asset Management — Overview." Principles and Terminology

ISO 15663-2:2001. 2001. "Petroleum and Natural Gas Industries — Life-Cycle Costing Part 2: Guidance on Application of Methodology and Calculation Methods."

ISO 15686-5. 2017. "Buildings and Constructed Assets." Service Life Planning. Life-Cycle Costing

Kanagaraj, G., S. G. Ponnambalam, and N. Jawahar. 2016. "Reliability-Based Total Cost of Ownership Approach for Supplier Selection Using

Cuckoo-Inspired Hybrid Algorithm." *International Journal of Advanced Manufacturing Technology* 84(5–8): 801–816. doi:10.1007/s00170-013-5545-1.

Kawauchi, Y., and M. Rausand. 1999. *Life Cycle Cost (LCC) Analysis in Oil and Chemical Process Industries*. Chiba: Toyo Engineering Corp.

Keeter, B. 2002. "Managing Availability for Improved Bottom-Line Results." *Maintenance Technology* 16 (4): 12–18.

Korpi, E., and T. Ala-Risku. 2008. "Life Cycle Costing: A Review of Published Case Studies." *Managerial Auditing Journal* 23(3): 240–261. doi:10.1108/02686900810857703.

Kumar, U. D., J. Crocker, T. Chitra, and H. Saranga. 2006. "Reliability and Six Sigma." *Springer Science & Business Media*, Jun 15.

Lad, B. K., and M. S. Kulkarni. 2008. "Integrated Reliability and Optimal Maintenance Schedule Design: A Life Cycle Cost Based Approach." *International Journal of Product Lifecycle Management* 3(1): 78. doi:10.1504/IJPLM.2008.019971.

LaLonde, B. J., and T. L. Pohlen. 1996. "Issues in Supply Chain Costing." *The International Journal of Logistics Management* 7(1): 1–12. doi:10.1108/09574099610805395.

Landscheidt, S., and M. Kans. 2016. "Method for Assessing the Total Cost of Ownership of Industrial Robots." *Procedia CIRP* 57: 746–751. doi:10.1016/j.procir.2016.11.129.

Lanza, G., and J. Rühl. 2009. "Simulation of Service Costs throughout the Life Cycle of Production Facilities." *CIRP Journal of Manufacturing Science and Technology* 1(4): 247–253. doi:10.1016/j.cirpj.2009.06.004.

Macchi, M., F. Kristjanpoller, M. Garetti, A. Arata, and L. Fumagalli. 2012. "Introducing Buffer Inventories in the RBD Analysis of Process Production Systems." *Reliability Engineering & System Safety* 104: 84–95. doi:10.1016/j.ress.2012.03.015.

Mandolini, M., E. Marilungo, and M. Germani. 2017. "A TCO Model for Supporting the Configuration of Industrial Plants." *Procedia Manufacturing* 11: 1940–1949. doi:10.1016/j.promfg.2017.07.339.

Manno, G., F. Chiacchio, L. Compagno, D. D'Urso, and N. Trapani. 2012. "MatCarloRe: An Integrated FT and Monte Carlo Simulink Tool for the Reliability Assessment of Dynamic Fault Tree." *Expert Systems with Applications* 39(12): 10334–10342. doi:10.1016/j.eswa.2011.12.020.

NATO – ALCCP-1 2008. "NATO Guidance on Life Cycle Costs."

Ouertani, M. Z., A. K. Parlikad, and D. McFarlane. 2008. "Asset Information Management: Research Challenges." 2008 Second International Conference on Research Challenges in Information Science June, IEEE, 361–370. doi:10.1109/RCIS.2008.4632126.

Parra, C., and A. Crespo. 2012. "Stochastic Model of Reliability for Use in the Evaluation of the Economic Impact of a Failure Using Life Cycle Cost Analysis. Case Studies on the Rail Freight and Oil." *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability* 226(4): 392–405. doi:10.1177/1748006X12441880.

Ramadan, S. Z. 2014. "Selection of Non-Repairable Series Systems' Components with Weibull-Life and Lognormal-Repair Distributions through Minimizing Expected Total Cost of Ownership Approach." *Modern Applied Science* 8(1): 104–112. doi:10.5539/mas.v8n1p104.

Rausand, M., and A. Høyland. 2004. *System Reliability Theory: Models, Statistical Methods, and Applications*. Vol. 396. John Wiley & Sons.

Roda, I., and M. Garetti. 2014. "TCO Evaluation in Physical Asset Management: Benefits and Limitations for Industrial Adoption." In *APMS 2014, Part III, IFIP AICT 440*, edited by B. Grabot, 216–223.

Roda, I., and M. Garetti. 2015. "Application of a Performance-driven Total Cost of Ownership (TCO) Evaluation Model for Physical Asset Management." In *9th WCEAM Research Papers. Lecture Notes in Mechanical Engineering*, edited by J. Amadi-Echendu, C. Hoohlo, and J. Mathew, 11–23, Cham: Springer.

Roda, I. and Macchi, M., 2018. "*A Framework to Embed Asset Management in Production Companies*." *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability* 232(4): 368–378. doi: 10.1177/1748006X17753501

Roy, R., R. Stark, K. Tracht, S. Takata, and M. Mori. 2016. "Continuous Maintenance and the Future – Foundations and Technological Challenges." *CIRP Annals* 65(2): 667–688. doi:10.1016/j.cirp.2016.06.006.

Saccani, N., M. Perona, and A. Bacchetti. 2017. "The Total Cost of Ownership of Durable Consumer Goods: A Conceptual Model and an Empirical Application." *International Journal of Production Economics* 183: 1–13. Elsevier: doi:10.1016/j.ijpe.2016.09.021.

Schuman, C. A., and A. C. Brent. 2005. "Asset Life Cycle Management: Towards Improving Physical Asset Performance in the Process Industry." *International Journal of Operations & Production Management* 25(6): 566–579. doi:10.1108/01443570510599728.

SEMI E35-0618. 2018. *Guide to Calculate Cost of Ownership (COO) Metrics for Semiconductor Manufacturing Equipment*. Brussels: SEMI International Standard.

Sinisuka, N. I., and H. Nugraha. 2013. "Life Cycle Cost Analysis on the Operation of Power Generation." *Journal of Quality in Maintenance Engineering* 19(1): 5–24. doi:10.1108/13552511311304447.

Taylor, W. B. 1981. "The Use of Life Cycle Costing in Acquiring Physical Assets." *Long Range Planning* 14(6): 32–43. doi:10.1016/0024-6301(81)90058-3.

Thiede, S., T. Spiering, and S. Kohlitz. 2012. "Dynamic Total Cost of Ownership (TCO) Calculation of Injection Moulding Machines." In *Leveraging Technology for a Sustainable World*, edited by D. Dornfeld, B. S. Linke, 275–280. Berlin: Springer.

Trienekens, J. H., and A. J. M. Beulens. 2001. "Views on Inter-Enterprise Relationships." *Production Planning & Control* 12(5): 466–477. doi:10.1080/09537280110042693.

VDI 2884. 2006. "Purchase, Operating and Maintenance of Production Equipment Using Life Cycle Costing."

VDMA 34160. 2006-06. "Forecasting Model for Lifecycle Costs of Machines and Plants."

Waeyenbergh, G., and L. Pintelon. 2002. "A Framework for Maintenance Concept Development." *International Journal of Production Economics* 77(3): 299–313. doi:10.1016/S0925-5273(01)00156-6.

Waghmode, L. Y., and A. D. Sahasrabudhe. 2012. "Modelling Maintenance and Repair Costs Using Stochastic Point Processes for Life Cycle Costing of Repairable Systems." *International Journal of Computer Integrated Manufacturing* 25(4–5): 353–367. doi:10.1080/0951192X.2010.551783.

Woodward, D. G. 1997. "Life Cycle Costing—Theory, Information Acquisition and Application." *International Journal of Project Management* 15(6): 335–344. doi:10.1016/S0263-7863(96)00089-0.

Wudhikarn, R. 2012. "Improving Overall Equipment Cost Loss Adding Cost of Quality." *International Journal of Production Research* 50(12): 3434–3449. doi:10.1080/00207543.2011.587841.

Xu, Y., F. Elgh, and J. A. Erkoyuncu. 2012. "Cost Engineering for Manufacturing: Current and Future Research." *International Journal of Computer Integrated Manufacturing* 25 (4–5): 300–314.