Measuring life cycle costs for complex B2B products: a novel, integrated and practical methodology across disciplines for pricing maintenance contracts

Matthias Schlipf, Carlos Keller, Fabian Lutzenberger, Stefan Pfosser, Andreas W. Rathgeber

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Measuring life cycle costs for complex B2B products

A novel, integrated and practical methodology across disciplines for pricing maintenance contracts

Matthias Schlipf
Department of Business Administration, Munich University of Applied Sciences, Munich, Germany
Carlos Keller
MAN Diesel and Turbo SE, Augsburg, Germany
Fabian Lutzenberger and Stefan Pfosser
FIM Research Center, University of Augsburg, Augsburg, Germany, and
Andreas Rathgeber
Institute of Materials Resource Management, University of Augsburg, Augsburg, Germany

Abstract

Purpose – The purpose of this paper is to develop a new interdisciplinary methodology to estimate the life cycle cost (LCC) of complex business-to-business products in order to price different types of maintenance contracts and show the applicability of the method in a case study. LCC comprise of initial capital costs as well of operation costs including probabilistic costs (such as the costs of repairs and spare parts), which are directly linked to the maintenance characteristics of the product.

Design/methodology/approach – The paper proposes an integrated and practical methodology that applies different approaches from different disciplines. Therefore, exponential distributions for failure rates in subsystems, World Bank logistics factors for logistics costs of spare part handling, as well implied credit default probabilities for the counterpart risk in full service leasing contracts are applied. In order to validate the applicability of the proposed methodology to practical problems, the tool is applied in three case studies.

Findings – The results of the case studies show that this methodology can be applied to analyze LCC structures of engines operating in various regions with regard to different types of engine maintenance contracts. The results also highlight the interplay of technical as well as financial risks.

Originality/value – Because the literature in maintenance engineering so far either proposes general frameworks to calculate LCC or concentrates on specific aspects of LCC, the paper contributes to the literature in presenting a new interdisciplinary methodology to estimate the LCC.

Keywords Life cycle costing, Risk factors, Lease contract, Maintenance services, Statistic model

Paper type Case study

Introduction

The transparent and comprehensive estimation of the life cycle costs (LCC) of products is becoming a must-have in business-to-business (B2B) markets. This is due to the fact that in B2B markets and in contrast to business-to-customer markets, products are always related to a service over their respective lifetimes.

Furthermore, decisions in B2B markets are mainly based on objective criteria (investment, availability, energy consumption, etc.) from a group of people (e.g. sourcing council), rather than on the subjective criteria (e.g. emotions for the product) from often only a single person (among many others, see Hutt and Speh, 2008). LCC also gains in importance as products become more complex, last longer and their costs increase. For example, large diesel engines (up to 100,000 hp) used in cargo vessels or power plants, or airliners providing seating for more than 500 people and undergoing 100,000 pressurization cycles, are highly complex engineered-to-order products with lifetimes of over 30 years. Despite being a multiple-million-Euro investment, operation costs (OPEX) easily overtake the initial capital costs (CAPEX) within a few operational years (in some cases, less than a year, see e.g. Asiedu and Gu, 1998). OPEX can include all types of operating fluids, consumables, maintenance, repair and modernization retrofits. This importance of costing is strengthened by the evolvement of new business models like maintenance and full service leasing contracts, which raise new opportunities to manufacturers in the after-sales market. Both contracts require the estimation of OPEX of complex B2B products, too. Thus, a method that can accurately estimate LCC of complex B2B products will inevitably benefit both customer and supplier and their strategic decisions. From the customers' perspective, such a method, which is implemented in a tool, is a commercial necessity since it can be used to compare LCC of different products in order to choose the most suitable solutions. From the suppliers' perspective, it is important to estimate the value of the LCC contracts as realistically as possible, due to the underlying technical and financial risks entailed in warranties.

However, looking in the literature, there are general frameworks for estimating LCC (see Dhillon, 2010; Fabrycky and Blanchard, 1991) or solutions for very special cases (see Bastian, 2015; Frangopol *et al.*, 1997; Lee *et al.*, 2012). In addition to that these models do normally not fully incorporate financial risks, operational risk and warranties. The latter are special challenges estimating LCC for real industry scenarios.

First, the estimation of LCC of complex B2B products, such as large diesel engines, huge airliners or power plants, is based on the determination of mean-time-between-failure (MTBF) and unplanned downtime (see e.g. Isaacson *et al.*, 1991; Frangopol *et al.*, 2004). However, in theoretical methodology, estimation of LCC is based only on a few spare parts or failure events (see Murthy and Blischke, 2000), which contradict the essence of B2B products – complex products with long lifetimes.

Second, the theoretical methodology solely inspects expected planned maintenance costs or warranty values. For practical applications, other factors need to be taken into account. These factors are, for example:

- service and maintenance costs due to long lifetimes of the products and non-geographically fixed maintenance and repair locations;
- logistic framework of the products;
- infrastructure of the provider for service and maintenance;
- country and credit risks; and
- insurance opportunities.

Third, integration of the service network of maintenance and repair providers must be foreseen and incorporated into LCC estimation. Fourth, maintenance contracts for B2B products in practical applications are often combined with split ownership structures that lead to leasing (see leasing in general Asiedu and Gu, 1998). This combination of split ownership is mostly not taken in consideration for LCC estimation.

Hence, we identify a research gap in developing a combination of methods from different areas by which the strategic decision as well the pricing of the maintenance contracts can be achieved. To close this gap we combine quantitative methodologies from engineering statistics and economics, risk management and finance, which take into consideration all given challenges. From the viewpoint of a practicing engineering management, the paper gives a mold for other applications. This is especially true due to the proof of the applicability of such a concept in a real live example. Herby the joint approach from different disciplines, which is typical for practical applications, supports a reliable estimation of the LCC. In addition to that and based on the proposed interdisciplinary methodology, we developed and implemented a software tool where pricing of the maintenance contracts can be calculated. Such a tool also gives insights in the driver of the LCC in case of complex B2B products.

To achieve these goals we propose in this study an integrated and practical methodology that applies different approaches from different disciplines. In order to validate the applicability of our proposed methodology to practical problems, we implement a tool applied in three case studies, in which the LCC structures of large diesel engines are analyzed. Such engines are usually used in marine applications or power generation. These case studies use data based on real industry scenarios.

The results show that this methodology can be applied to analyze LCC structures of engines operating in various regions (i.e. Europe, Africa and Asia) with regard to different types of engine maintenance contracts. The three types of contracts investigated are as follows:

(1) basic service maintenance (BSM);

(2) full service maintenance (FSM); and

(3) leasing (LS).

These contract types are dependent on the degree of risk sharing between engine supplier and end customers. Figure 1 presents the parameters considered in the three defined contracts. Customers who choose BSM buy the engine and pay an annual fee. In return, suppliers bear planned maintenance costs. Customers who select FSM also buy the engine and pay an annual fee. However, suppliers pay for all engine unplanned maintenance costs as well. It should be noted that unplanned maintenance costs are possible costs of maintenance service that are not foreseen during extensive products testing and validation. Finally, customers who prefer LS lease the engine and pay solely a fee per engine operating hour.

To detail our research, we structure the remainder of our paper as follows: the next section contains a literature review of state-of-the-art LCC methodologies. The third section presents our proposed methodology. The section "case study" shows analysis of and results for the case studies in which the proposed methodology is applied. In this section, we also show the usage and strategic benefit of such a methodology from customers' perspective. The section "summary" concludes with the summary and recommendation/suggestions for future work.

Literature review

Our literature review of LCC methodologies shows that the approach at hand needs to be enhanced with different methodological aspects from different disciplines, especially from risk management and finance, in order to deal with special challenges (Introduction). For example, to estimate LCC of large diesel engines based on real industry scenarios, example parameters to be taken into consideration include:

- quantification of planned and unplanned downtime of highly complex products;
- integration of logistical aspects based on geographical operational location of the products;
- integration of vessel movements from one location to another during its lifetime;
- integration of financial and especially country risk;

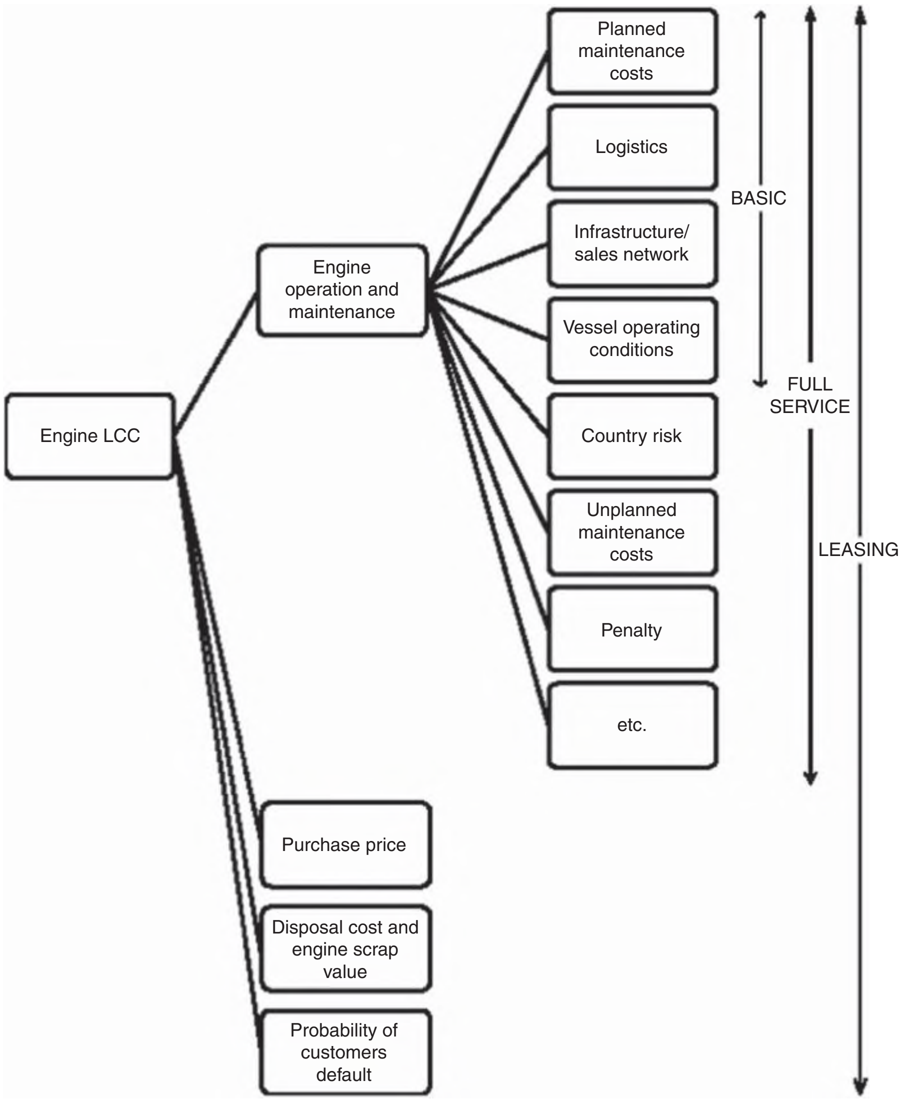


Figure 1.
The graph depicts technical and financial risks and costs included in the calculation of engine LCC for three defined contract types

- consideration of insurance cost in unplanned maintenance; and
- consideration of credit risk, in the case of LS.

To be more precise, the central idea of LCC according to Dhillon (2010, p. 29), Fabrycky and Blanchard (1991) or Qin *et al.* (2012) is to include in the analysis all costs incurred during the product life cycle. Due to the fact that the life cycle under inspection is relatively long, we account for the time value of money by applying the concept of discounted cash flows. In addition, the risk component must be elaborated upon. Deriving our methodology from risk management literature, e.g., Crouhy *et al.* (2001, p. 370), we differentiate between forecasted cash flows and deviation from the expectation. The latter is also called "unexpected risk" or "loss," in parts of the risk management literature (e.g. Hull, 2012, p. 260; Saita, 2007, p. 60) or real risk in literature of decision theory (e.g. Ingersoll, 1987, p. 114). Furthermore, the forecasted or expected cash flows are also called "expected risk" or "expected loss" and are estimated by their expected value or mean. We include both types of risks in our methodology. Altogether, we combine methodologies to calculate values for BSM, FSM or LS, in order to calculate the rate according to Dhillon (2010, p. 19) for LCC issues, or to the more general situation Copeland *et al.* (2003, p. 697):

$$Fee = \sum_{t=0}^{T} \frac{E(CF_t)}{(1+R_{RF}+R_{RP})^t} \cdot \frac{(1+R_{RF}+R_{RP})^T \cdot (R_{RF}+R_{RP})}{(1+R_{RF}+R_{RP})^T - 1}. \quad (1)$$

The goal here is to determine the expected cash flow $E(CF_t)$, and the appropriate discount factor, the risk-free interest rate R_{RF} as well as the risk premium R_{RP}. In Equation (1), t and T represent time and contract duration, respectively. Starting with the numerator of the first term, we include all cash flows or costs in the calculation. According to Asiedu and Gu (1998), the B2B products inspected can be classified as large-scale products, therefore their maintenance must be considered in detail. In this paper, research and development costs as well as production and construction costs are not considered when standard maintenance contracts are priced. In case of LS, these components are inherently included in the selling price.

Hence, the focus is on maintenance costs and partly on operations and retirement costs. Therefore, we concentrate on planned and unplanned costs for which a service model analysis concept exists, e.g., Appel *et al.* (2014) or Gershenson and Ishii (1993). To this end, our methodology consequently addresses maintenance plans (Gershenson and Ishii, 1993; Wawerla, 2007, p. 34). Due to this fact, we are able to use an intercompany database consisting of spare parts, prices, MTBF, etc. (e.g. Dhillon, 2010; Behrendt *et al.*, 2012 in the engineering literature). If such empirical data are not available, expert judgment (e.g. from experienced service and test engineers) or analogies of functional comparable components for which MTBFs and maintenance data are known (e.g. data from a larger engine) should be used as proposed by Wawerla (2007). Following the suggestions of Asiedu and Gu (1998) or Lanza *et al.* (2013) as closely as possible, we analyze the expected cash flow separately for each spare part.

In our case of a complex B2B service contract, we additionally take into account that service or maintenance is provided worldwide. This problem is only addressed in a few cases in LCC literature. In his review in Sherwini (2000), the author emphasizes this connection of maintenance management and logistics. However, most of the literature originates from operational research and focuses on the optimal level of inventories and placement of nodes in a service network (see for an overview, e.g. Huiskonen, 2001; Kennedy *et al.*, 2002). Because the nodes and corresponding levels are given in our situation, our focus lies on the calculation of costs depending on the performance of the network.

Thus, a measure for the performance of these networks is inevitably needed. A rich body of literature, among others Fawcett and Cooper (1998) as well as Murphy and Daley (2001), evaluate private and public networks (for a review see Chow *et al.*, 1994). For our practical applied LCC, we concentrate on public network as well as on the supplier's logistics network information. Hence, we follow the methodologies of Murphy *et al.* (1993) and Murphy and Daley (1999), leading to the Logistics Performance Index (LPI) of the World Bank (see Arvis *et al.*, 2014). The latter is supplemented with the help of additional supply networks data (see later). Altogether, in our methodology the quality of the logistic network measured by the LPI is one of the factors driving the maintenance cost.

As previously mentioned in the Introduction, FSM includes unplanned engine maintenance costs. Thus, in order to fulfill these requirements, we include unplanned corrective costs in the calculation as well. In this field, there exist different methodologies developed for construction engineering (see e.g. a review by Frangopol *et al.*, 2004). Most of these authors (e.g. Sherwini, 2000; Frangopol *et al.*, 1997) focus on optimal maintenance plans, partly under a stochastic environment. Among them an approach which is close to us is the recent method of Seif and Rabbani (2014), which find the minimum LCC of one machine with several components by means of a parallel machine replacement problem. In so doing, they ground their research on a literature stream on machine replacement under different conditions like budgeting or demand constraints (see Keles and Hartman, 2004; Jones and Zydiak, 1993).

One of the first authors to include stochastic occurrence of failures in LCC is Bras and Emblemsvag (1996), extending their work in Emblemsvag and Bras (1994) by inclusion of uncertainties. Moreover, such uncertainty is mostly driven by engineering and physical laws, which depend to an extent on well-ordered cause and effect relationships, and are unlike economic laws depending on reactions of people (Asiedu and Gu, 1998). To this extent, our methodology is comparable to that of Damnjanovic and Zhang (2008) and Scanff *et al.* (2007), among others. These works calculated the costs of unplanned maintenance in a stochastic environment using Exponential or Weibull distributions for the time to failure (see Kayrbekova *et al.*, 2011; Sinisuka and Nugraha 2013; Sherwini, 2000).

These distributions are folded when the system depends on several components or spare parts with the help of a failure tree. However, for calculation of the present value of the costs, simple methodologies are applied in a risk neutral setting, if at all (see Frangopol *et al.*, 1997; El Hayek *et al.*, 2005; Damnjanovic and Zhang, 2008; Lin *et al.*, 2013). In this paper, we address the problems with the help of a risk premium, as described in the following paragraph.

It is assumed that an insurance company covers some parts of the unplanned maintenance costs. To address this problem, classical insurance calculations like Mikosch (2009) and methodologies from warranties like Isaacson *et al.* (1991), Murthy and Blischke (2000) or Sahin and Polatogu (1995) can be consulted. Due to the special construction of the insurance in this sector, we apply a methodology comparable to Mikosch (2009) leading to reduced unplanned maintenance costs in connection with additional insurance premiums.

As depicted in Equation (1), the denominator of the first factor contains the two additional components, namely, risk and time value of money. The latter addresses the discount factor (interest rate R_{RP}), which is more or less a standard methodology in LCC literature (see Dhillon, 2010, p. 11) and derived in classical finance literature (see Copeland *et al.*, 2003, p. 881). The only outstanding issue in discounting is the distinction between real and nominal interest rates as well as real and nominal cash flows (costs). We decide to follow the suggestion of Brealey *et al.* (2011, p. 87), and calculate on the nominal basis.

To account for risk, risk management literature proposes almost exclusively to adjust the interest rate with a risk premium R_{RP} for the market risk (see Copeland *et al.*, 2003, p. 505; Hull, 2012, p. 7). The premium is derived from the Capital Asset Pricing Model leading to the classical Weighted Average Cost of Capital (WACC) methodology. In addition, country risk according to Damodaran (2003) is included in this methodology. However, this methodology does not directly apply to the pricing of maintenance contracts, because a higher market risk generally lowers the present value of the first term. The origin of this problem lies in the fact that the maintenance contract must be kept as a liability, insofar as the supplier is obligated to deliver the service. Consequently, the rules for the valuation of liabilities, e.g., those of IAS 19, are applicable. Besides some criticism (see Rhiel, 1997 in the special case of retirement plans), the concept itself (see e.g. Towers and Watson, 2011) is applicable, provided adjustments regarding the discount and the annuity factors have been made.

In contrast to BSM and FSM, the lessor of the LS normally receives the cash flows to finance the leased asset during the lease periods. Consequently, LS can be kept and valued as an asset. Due to the absence of embedded options in the inspected LS, the standard methodology from Myers *et al.* (1976) is applicable. However, because the lessee is obligated to pay a fee, an eventual bankruptcy of the lessee harms the lessor. To account for that credit risk, the well-known methodology of Grenadier (1996) exists in the literature. Again, due to the fact that LS examined does not include embedded options, the model given by Grenadier (1996) simplifies to the model of Jarrow and Turnbull (1995), and we thereby apply their model in this study (see for an overview Lando, 2004).

In summary, we have incorporated many real industry requirements for accurate LCC calculations into a new model based on a bunch of available theoretical methodologies in the literature. Thereby in the next section, we show our contribution in using and combining different methodologies from engineering and financial mathematics into an applicable model to analyze the LCC structure of complex B2B products. Our work fills the gap, which we observed during our literature review. Hence, our work enriches the current LCC methodology with other methodological aspects from different disciplines, such as engineering, risk management and finance.

Methodology

In this section, we introduce calculations underlying the three previously defined contract types (A, B and C), as mentioned in previous sections and Figure 1. In our proposed methodology, we devote special focus to the different kinds of risks that these three contracts are exposed to, and how these risks are considered.

Before introducing the calculus, we have to present some technical details of the considered B2B product. This is necessary, because the characteristics of the product determine lifetime of the product and maintenance plans. Looking at the maintenance plan, it comprises relevant parts and components with their specific time between overhaul (TBO). Additionally, in order to calculate possible unplanned repair costs, detailed information regarding the meantime to failure or failure distributions of the product's parts and components have to be available. Based on this information and, for example, by means of failure trees, average expected failures of the B2B product can be calculated and evaluated. Via failure trees, a top-down analysis of all possible undesired states of a system via Boolean logic is performed. Thus, the probability of a failure for the system and each of its subsystems down to the lower-level elements is calculated. If such empirical data are not available, expert judgment (e.g. from experienced service and test engineers to estimate MTBF and downtime) or analogies of functional comparable components for which MTBFs and maintenance data are known (e.g. data from a larger engine) can be used. In the following, we assume that the described information regarding the B2B product is available or can derived, building the basis for the calculation of the three defined contract types.

Basic service maintenance (BSM)

All planned costs are included in BSM. These planned costs comprise fixed annual costs (e.g. for remote monitoring or fuel and lube oil analyses) as well as planned costs for consumables and labor. The latter is based on the engine's maintenance plan and differs on a yearly basis. We seek to calculate a constant annual fee, paid by the customers. For this purpose, we first calculate the net present value (*NPV*) of all (expected) costs:

$$NPV_{BSM} = \sum_{t=1}^{T} \frac{\left[C_{fix} + \left(C_{con,t} + C_{lab,t}\right) \cdot (1+l)\right] \cdot (1+i)^t}{(1+R_{RF})^t} - U, \tag{2}$$

where C_{fix} denotes fixed annual costs (e.g. lube oil analysis), $C_{con,t}$ are the planned costs for consumables in t and $C_{lab,t}$ represents the planned labor costs in t. Moreover, l denotes a logistics (risk) factor that adjusts the costs for consumables and labor by taking into account a country's infrastructure, and i denotes the inflation rate, assumed to be constant through time. Finally, U denotes a potential upfront payment the customer may have to pay, R_{RF} represents the one-year risk-free interest rate, which we also assume to be constant through time, and T is the contract duration (see for an overview of variables in use Table I).

In order to compute the annual fee to the customers (see also Equation (1)), we multiply NPV_{BSM} by an annuity factor (e.g. Copeland *et al.*, 2003, pp. 883-885):

$$Fee_{BSM} = NPV_{BSM} \cdot \frac{\left(1+WACC_{adj}\right)^T \cdot WACC_{adj}}{\left(1+WACC_{adj}\right)^T - 1}, \tag{3}$$

where $WACC_{adj} = R_{RF} + R_{RP}$ denotes the supplier's adjusted WACC. We address a selection of these variables in more detail in the following, starting with parameters contained in the numerator of Equation (2).

First, the variable $C_{con,t}$ is computed considering the engine maintenance plan and frequency. The frequency depends on the initial state (in case of a used engine), planned annual operating hours and the load profile of the engine. We employ various reference-load profiles for different engine operations – each reflecting the real industry applications – e.g. a ferry with many high

Base case and BSM		FSM		LS	
VAR	Description	VAR	Description	VAR	Description
$C_{con,t}$	Planned costs for consumables in t	$a_{cov,x,t}$	Average share covered by the insurance	C_{ins}	Installation costs for the engine
$C_{fix,t}$	Fixed annual costs	C_{ic}	Initial costs for checking the engine	λ	Probability of default
$C_{lab,t}$	Planned labor costs in t	$C_{u,t}$	Unplanned failure costs	MV	Market value of the engine
CF_t	Cash flow	$C_{fail,a,t}$	Costs associated with all failure events in t above the threshold and exceeding the maximum number of failure events	$P_{pur,t}$	Purchase price for the engine at the end of the contract
Fee	Fee	$C_{fail,b,t}$	Costs associated with all failure events in year t below the insurance threshold		
l	Logistics factor	$C_{pan,j}$	Penalty due to the engine's unavailability in case of failure		
$l_{\min}$, $l_{\max}$	Minimum and maximum logistics factor	$\overline{f_{a,t}}$	Average probability with which a failure event above the threshold occurs		
L_{sup}	Supplier-specific logistics (risk) factor	f_j	Average failure probability of item j per 1,000 operating hours		
L_w	World bank logistics index	$Fee_{ins,t}$	Insurance fee		
i	Inflation rate	$H_{op,t}$	Number of operating hours in year t		
$N_{hub,h}$	Number of the active hubs in the closest port or city in country h	J	Number of items that potentially fail		
NPV	Present value of expected costs	N_{cov}	Maximum number of covered annual failure events		
R_{RF}	Risk premium	$p(N_{eve,a} = x_t)$	Conditional probability for x_t failure events		
R_{RP}	One-year risk-free interest rate	TH_{ins}	Insurance threshold		
T	Contract duration	x_t	Number of failure events		
U	Potential upfront payment				
$WACC_{adj}$	Weighted average cost of capital				

Table I.
Notation of the variables (VAR) applied in the three different model basic service maintenance (BSM), full service maintenance (FSM), and Leasing (LS)

load operations and a tugboat with many low load operation (= idle mode). Thereby, deviations from these reference-load profiles – and the underlying differences in engine performance and in annual running hours – lead to an adjustment of the maintenance frequencies.

Second, $C_{lab,t}$ comprises the actual working costs, which consider country- and skill-level-specific pay rates, as well as the number of required workers per skill level. We include additional costs such as hotel costs (regarding country-specific accommodation costs) as well as travel costs (taking into account country- and skill-level-specific pay rates, actual travel costs and traveling time) for each required worker.

Third, the logistics (risk) Factor l: the logistics factor is a mark-up because of bad logistics performance. It depends negatively on the logistics performance of a country as well as on the individual performance of a company's logistics network. It is obtained as follows:

$$l = \beta_0 + \beta_1 \cdot (L_w + L_{sup}), \tag{4}$$

where L_w denotes the World Bank (2014) LPI, which "reflects perceptions of a country's logistics based on […] quality of trade- and transport-related infrastructure, the ability to track and trace consignments, and the frequency with which shipments reach the consignee within the scheduled time." Further, L_w is standardized by the World Bank between the values of 1 and 5. L_{sup} represents a supplier-specific logistics (risk) factor, computed as follows:

$$L_{sup} = 4 \cdot \frac{N_{hub,h}}{\max_{k \in countries} N_{hub,k}} + 1 \text{ with } \max_{k \in countries} N_{hub,k} > 1. \tag{5}$$

In the above equation, $N_{hub,h}$ denotes the number of the suppliers' active service hubs in the closest port or city in country h in which the engine is operated, and max $N_{hub,k}$ represents the maximum number of hubs that the supplier operates in all countries. As more hubs exist in a country the higher the value becomes. However, L_{sup} does not account for the size of the country in that sense that more hubs are needed in a country with more coastal line and more ports than in a landlocked country. Due to construction, the equation scales L_{sup} in a range from 1 to 5, in order to make it comparable to L_w. Equation (4) is the standard formula for linearization, where l is the dependent variable, L_w+L_{sup} the independent variable, and β_0 and β_1 are free parameters, computed as follows:

$$\beta_1 = \frac{l_{\min} - l_{\max}}{10-2} = \frac{l_{\min} - l_{\max}}{8} \text{ and } \beta_0 = l_{\max} - 2\beta_1, \tag{6}$$

where $l_{\min}$ equals 1 in the case that L_w+L_{sup} shows its maximum possible value (a value of 10), that is, the country shows the best logistic conditions. A reasonable value for $l_{\min}$ is 0, indicating a 0 mark-up on the planned costs for consumables and labor. The term $l_{\max}$ denotes the value of l in the case that L_w+L_{sup} shows its minimum possible value (a value of 2), i.e., the country shows the worst logistic conditions. According to expert estimations, an appropriate value for $l_{\max}$ seems to be 0.1, leaving us with a 10 percent mark-up on the planned consumables and labor costs. Nevertheless, the value of $l_{\max}$ can be adjusted to specific conditions, depending on the application. In case of $l_{\max} = 0.1$ and $l_{\min} = 0$, β_1 is −0.0125 and β_0 is 0.125. Hence, in case of a perfect network ($L_w = L_{sup} = 5$) l is 0, which implies now additional cost from the logistic factor. Otherwise, if the network is bad ($L_w = L_{sup} = 2$) $l = 0.1$ leading to 10 percent additional costs. The logistics factor adjusts the costs for consumables and labor, since these costs are influenced by the logistics of the country the engine is operated in, and considers risks associated with country-specific infrastructure, access and logistics.

In addition to that i is included in Equation (2) to take into account inflation, that is, the expectation that prices rise through time due to inflation (calculated on a nominal basis). Finally, U incorporates the possibility that the customer provides the supplier with an initial upfront payment, thereby reducing the annual maintenance fee.

We next regard the denominator of Equation (2) along with Equation (3). As described, typical application of the NPV methodology is to measure the profitability of an investment, using a risk-free interest rate plus a risk premium. Thereby, the risk premium can decrease the NPV: the higher the risk, the smaller the NPV (e.g. Copeland *et al.*, 2003). However, since we do consider future costs, a higher risk premium would decrease the expected future risk-adjusted costs, and consequently increase the value of the investment. For this reason, such a risk premium in the denominator of the NPV calculation appears to be meaningless. Hence, we only include the risk-free rate R_{RF} in the denominator of Equation (2), which solely adjusts the costs embodied in the numerator by the time value of money. We then consider the risk of these costs in the annuity factor of Equation (3), by using the standard WACC of the supplier plus an additional country-specific risk premium ($WACC_{adj} = R_{RF} + R_{RP}$). By introducing an additional risk premium, this adjustment incorporates country-specific risks associated with the investment and trading environment, political violence, the general business relationship with the host country, as well as sovereign credit risk.

Full service maintenance (FSM)

Unplanned services in addition to planned costs incorporated in BSM are also considered in FSM. We again first calculate the NPV of all expected future costs, which is an extension of Equation (2):

$$NPV_{FSM} = C_{ic} + \sum_{t=1}^{T} \frac{\left[C_{fix} + \left(C_{con,t} + C_{lab,t} + C_{u,t}\right) \cdot (1+l)\right] \cdot (1+i)^t}{(1+R_{RF})^t} - U, \tag{7}$$

where C_{ic} denotes the initial costs for checking the engine (in case it is used), and $C_{u,t}$ represents unplanned failure costs in year t. As for the planned costs, we multiply $C_{u,t}$ by the logistics factor as well as by inflation. Analogous to the calculation of the fee for the BSM, the annual fee is again computed by multiplying NPV_{FSM} by the annuity factor as depicted in Equation (3) (see for an overview of variables in use Table I).

Our model considers the option to insure costs associated with a stipulated maximum number of failure events, whose costs exceed an agreed threshold. For the insurance contract, we used a real-world example. However, it is one of several ways to model an insurance contract and it is optional to include the insurance contract in the model. Accordingly, the supplier has to pay for all failure events below this threshold as well as for all failure events that exceed the predefined maximum number of failure events covered by insurance, as well as an insurance fee. Consequently, $C_{u,t}$ comprises three components:

$$C_{u,t} = C_{fail,b,t} + C_{fail,a,t} + Fee_{ins,t}, \tag{8}$$

where $C_{fail,b,t}$ denotes costs associated with all failure events in year t below the insurance threshold, $C_{fail,a,t}$ represents costs associated with all failure events in year t above the threshold and exceeding the maximum number of failure events (ergo not covered by insurance), and $Fee_{ins,t}$ denotes the insurance fee in year t. As a first step, we compute the costs for failure events below the insurance threshold:

$$C_{fail,b,t} = \sum_{j=1}^{J} \frac{f_j}{1,000} \cdot H_{op,t} \cdot \left(C_{con,j} + C_{lab,j} + C_{pen,j}\right), \tag{9}$$

$$\forall j \text{ where } C_{con,j} + C_{lab,j} + C_{pen,j} < TH_{ins},$$

where f_j denotes the average failure probability of item j per 1,000 operating hours, J is the number of items that potentially fail, $H_{op,t}$ is the number of operating hours in year t and TH_{ins} denotes the insurance threshold. Moreover, the unplanned services associated with a given failure item j include costs for unplanned consumables and labor, $C_{con,j}$ and $C_{lab,j}$, as well as a penalty $C_{pen,j}$ which the supplier may have to pay to the customer due to the engine's unavailability in case of failure (depending on downtime hours). Thereby, the expected downtime depends on the respective failure item j. The costs for consumables and labor are costs occurring if item j fails. All other terms are calculated similarly to those of the planned maintenance costs.

We compute $C_{fail,a,t}$ in a second step. An exact computation of these costs would be difficult to implement in practice and would entail long computation times. For this reason, we use an approximation in order to make our model practically applicable. To analyze the error made we computed for several cases the true $C_{fail,a,t}$ with our approximation and found out that the approximation error is tolerable (mean below 5 percent). In particular, the average probability with which a failure event above the threshold occurs in a given year is computed as follows:

$$\overline{f_{a,t}} = \frac{1}{J} \cdot \sum_{j=1}^{J} \frac{f_j}{1,000} \cdot H_{op,t}, \tag{10}$$

$$\forall j \text{ where } C_{con,j} + C_{lab,j} + C_{pen,j} \geqslant TH_{ins}.$$

Using this average probability, we calculate the probability that x_t failure events happen within year t with $x_t = \{0, 1, 2, \ldots, J_a\}$, where J_a is the maximum number of events that cause costs above the threshold, on the basis of the binomial distribution (e.g. Çinlar, 2011, p. 89):

$$p\left(N_{eve,a,t} = x_t\right) = b\left(x_t \middle| \overline{f_{a,t}}, J_a\right) = \binom{J_a}{x_t} \cdot \overline{f_{a,t}}^{x_t} \cdot \left(1 - \overline{f_{a,t}}\right)^{J_a - x_t}, \tag{11}$$

where $p(N_{eve,a,t} = x_t)$ is calculated as a conditional probability for x_t failure events within year t. Then, for simplicity, we compute the average share covered by the insurance for a given failure event, which depends on the number of failure events in year t and the maximum number of covered annual failure events (N_{cov}):

$$a_{cov,x,t} = \begin{cases} 1 & \text{if } N_{cov} \geqslant x_t \\ \frac{N_{cov}}{x_t} & \text{if } N_{cov} < x_t \end{cases}. \tag{12}$$

On this basis, we calculate the expected percentage with which expected failure events in year t are covered by insurance:

$$a_{cov,t} = \sum_{x=0}^{J_a} p\left(N_{eve,a,t} = x_t\right) \cdot a_{cov,x,t} \tag{13}$$

Finally, we obtain the expected costs above the insurance threshold for year t on the basis of the failure probabilities for failure events above TH_{ins} and the term $a_{cov,t}$:

$$C_{fail,a,t} = \sum_{j=1}^{J} \frac{f_j}{1,000} \cdot H_{op,t} \cdot \left(C_{con,j} + C_{lab,j} + C_{pen,j}\right) \cdot \left(1 - a_{cov,t}\right), \tag{14}$$

$$\forall j \text{ where } C_{con,j} + C_{lab,j} + C_{pen,j} \geqslant TH_{ins}.$$

Thus, it is possible to estimate a quantity for events of unplanned costs exceeding the coverage of a particular insurance (policy).

Leasing (LS)

The basic idea of LS is that a customer does not purchase the engine but pays a fee for using it, similar to standard lease contract in B2B applications (e.g. Copeland *et al.*, 2003). We differentiate between marine and power applications in order to cope with their peculiarities. In marine applications, engines are fixed in one vessel and consequently bound to its specific application during its whole lifetime, while for power applications, an engine may be employed at different sites of operation during its lifetime. Accordingly, LS for marine applications considers all planned and unplanned costs, engine operation costs, market value of the new engine, installation costs, default probability of the customer, as well as the engine's purchase price and scrap value. In contrast, LS for power applications additionally incorporates the engine's mobilization costs, storage costs for the share of time per year in which the engine is stored at the supplier's premises, as well as the engine's expected market value at the end of its lifetime.

The following paragraphs present the computation of the leasing fee associated with LS for marine applications. The methodology can also be extended to power applications. We first compute the NPV of all expected future payments supplier must pay or earn as a basis for the calculation of the fee later on:

$$NPV_{LS} = -MV - C_{ins} + U + \frac{P_{pur,T} \cdot (1-\lambda)^T}{\left(1+WACC_{adj}\right)^T}, \tag{15}$$

$$\sum_{t=1}^{T} \frac{H_{op,t} \cdot Fee_{LS} \cdot (1-\lambda)^t + SV \cdot \lambda \cdot (1-\lambda)^{t-1}(1+i)^t - C_t \cdot (1-\lambda)^{t-1}}{\left(1+WACC_{adj}\right)^t},$$

where MV denotes the market value of the engine in $t = 0$, C_{ins} the installation costs for the engine, SV the scrap value of the engine and U a potential upfront payment. To cover income payments during the contract duration, the leasing fee is multiplied by the annual operation hours (H_{op}), and the purchase price for the engine at the end of the contract ($P_{pur,T}$) is also added (see for an overview of variables in use Table I). The annual costs (C_t) cover all costs from the FSM contract, including engine operation costs. Following credit risk models (e.g. Lando, 2004), the calculation of LS takes into consideration that the customer can default with a default probability λ, assumed to be constant over time and equal to the weighted long-term average of the one-year global default rate of its Standard & Poor's rating. Thus, we assume that a customer who defaults in a given year will not pay the fee in that year, but costs for the supplier will incur nevertheless. The assumption that λ is constant over time is debatable. Especially for long-term lease contracts, the default probability might change over time. However, to challenge this assumption we alternated the default risk in our case study.

Moreover, the supplier recovers the engine, but sustains the costs associated with demounting it. We then solve Equation (15) for the leasing fee per operating hour:

$$Fee_{LS} = \frac{MV + C_{ins} - U \pm \left(\left(P_{pur,T} \cdot (1-\lambda)^T\right) / \left(1+WACC_{adj}\right)^T\right) + \sum_{t=1}^{T} \left(\left(C_t \cdot (1-\lambda)^{t-1} - SV \cdot \lambda \cdot (1-\lambda)^{t-1} \cdot (1+i)^t\right) / \left(1+WACC_{adj}\right)^t\right)}{\sum_{t=}^{T} \left(H_{op,t} \cdot (1-\lambda)^t / \left(1+WACC_{adj}\right)^t\right)}. \tag{16}$$

Finally, the leasing fee per kWh is computed by dividing the leasing fee by the vessel's kW per operating hour.

Case study, analysis and result

In our case study, we investigate the LCC structure and use a sensitivity analysis to investigate the effects of parameters variations in the overall LCC. We analyze how different components from different disciplines interact and how each of them is indispensable to the LCC calculation. The central idea of our case is not to analyze the application of our methodology via a developed tool in detail and validate our method. Contrarily, we only want to show the applicability of our methodology and give some hints for the central drivers of the cost.

This section is divided as follows: first, we present the tool developed as an application of our proposed methodology and used in our analysis. Subsequently, we introduce the data and scenarios utilized in this study. Next, we discuss in detail the results of each scenario and their comparisons across the different scenarios. Finally, we present the results of the sensitivity analysis.

Our methodology is applied to calculate LCC of a complex B2B product – a large diesel engine for marine applications. Nevertheless, the results of this study can be extended to other products in B2B markets, such as the airline industry.

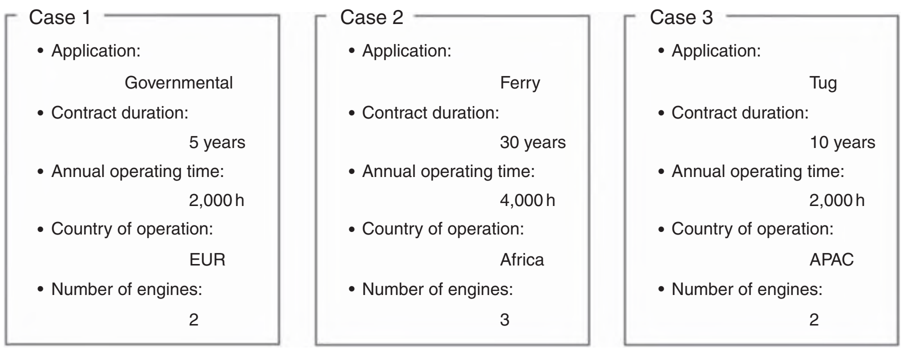
As mentioned before, one characteristic of B2B products is their complexity. Thereby, the considered large diesel engine consists of more than 1,000 different parts assembled within more than 80 subsystems. Within the maintenance plan for high load applications such as ferries, there are more than ten major maintenance intervals during the considered engine lifetimes of 30 years.

Thereby, the smallest maintenance comprises of more than 10 parts and more than 6 single tasks, whereas the biggest maintenance consists of more than 100 parts and more than 20 single tasks. Regarding the unplanned maintenance costs, we used 10 years maintenance data records related to critical components of the engine.

Figure 2 presents three industry scenarios and engine-specific technical parameters used. For each scenario, three defined contract types are investigated. It can be noted that engine choices vary with vessel type, annual operating time and operational region, while their service and maintenance are highly dependent on the contract type and duration. The variable financial risks investigated in this case study include labor costs, credit and country risks and risks from logistic networks.

The proposed methodology is implemented in Microsoft Excel 2007 VBA programming language. Microsoft Excel 2007 with the VBA programming language is chosen for its simplicity and fast development time. In the tool implementation, we collect data from multiple databases (i.e. maintenance statistics, country risk rating tables, LPI tables, etc.) and directly link them to the LCC tool.

For the three defined contracts, BSM, FSM and LS, analysis of LCC structures is performed by breaking down the overall LCC into cost per year and per engine maintenance intervals according to Equation (2), Equation (7) and Equation (16).



Note: EUR and APAC represent Europe and Asia Pacific, respectively

Figure 2.
Three industry scenarios that are used in the validation study

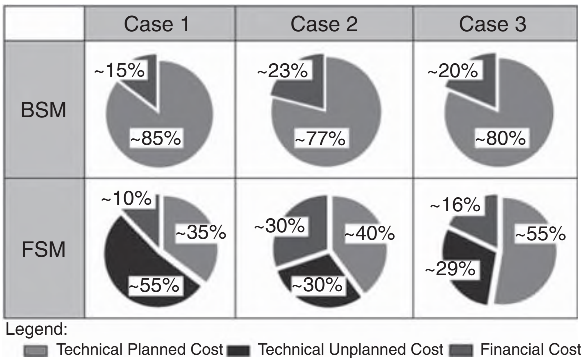
For BSM, we analyze only planned maintenance costs associated with engine operation and maintenance. For FSM, we include both planned and unplanned maintenance costs (see for the latter Equation (7)). Further, for LS, we extend the calculation by accounting for the investment accompanying leasing (Equations (15) and (16)).

These costs include market and scrap values of the engine, installation costs and purchase price at the end of the lease period. In our case study, the engine scrap value is used for the buy-back purchase price. Additionally, customer credit risk determines the leasing fee. In this respect, we use an implied default probability λ derived from the credit spread for a customer rated "A" by S&P (average customer rating). Our methodology can also be extended to variable customer ratings where historical default frequencies are used.

We present the results of our study as percentage pie charts in order to highlight the contributions of various technical and financial risks with respect to the overall annual total fee. As shown in previous section, the following risks are aggregated into technical planned, technical unplanned and financial costs, respectively:

- For technical risk, we take into account fixed annual costs C_{fix}, planned costs for consumables and labor, $C_{cont,t}$ and $C_{lab,t}$, respectively, as well as initial costs for checking the engine C_{ic} into the technical planned costs. On the other hand, for the technical unplanned costs, we consider the insurance premium $Fee_{ins,t}$ and the unplanned failure costs $C_{u,t}$.
- Financial risk, we aggregate inflation i, logistic factor l and customer credit risk λ (in case of LS) into the cost calculation.

The results for all three case studies are presented in Figure 3. For BSM, it is shown that technical planned costs are dominant and vary insignificantly from Case 1 to Case 3. In Case 1, due to a short travel duration between European countries, the accumulating factor for logistics costs plays a minor role. In general, developed countries provide an efficient road and air transportation system that reduces financial risks in logistics (see parameter l, Equation (2)). Subsequently, this translates to insignificant logistic costs regardless of the location of the vessels.



Notes: Data on the pie chart are displayed as percentages of the annual total maintenance costs. Planned costs include labor and spare part costs. Unplanned costs include failure cost not covered by insurance and insurance fees. Financial costs include logistic and inflation costs for planned and/or unplanned maintenance costs. SM and FSM represent basic service and full service maintenance, respectively

Figure 3.
Results of the analysis for Cases 1–3 in percentage pie charts

Furthermore, in reference to BSM, a slight variation can be noted in financial costs (a variation of 15 to 23 percent from Case 1 to Case 3, respectively). In Case 1, given that the operational area is Europe, this results in a low accumulation factor for inflation i. In Case 3, the operational area is APAC and the contract duration is doubled with respect to Case 1. Thus, costs related to factors such as inflation and logistics exceed the corresponding costs observed in Case 1. In Case 2, a combination of a distant operational area (Africa), i.e., far from Europe, and a very long contract duration (30 years) results in the highest increase in accumulating factors like country risk, inflation and logistics; hence, the highest financial costs are observed in Case 2.

For FSM (see Figure 3), a variation in technical planned, technical unplanned and financial costs can be observed in all the case studies investigated. Some patterns can be drawn from the observations. Comparing technical planned and financial costs, we note that, in all cases, financial costs increase in relation to technical planned costs. This is due to the fact that financial costs are, by nature, modeled as a factor in an algebraic sense. Consequently, these costs are related to technical planned as well as to technical unplanned costs.

Furthermore, looking at technical unplanned costs, their proportions vary from 55 to 29 percent from Case 1 to Case 3, respectively. For Case 1, the huge proportion of technical unplanned costs is due to a short contract duration of five years (see Figure 2). The engine long TBO translates to no major maintenance being required within the short contract duration. However, unplanned maintenance may occur, and this yields a high proportion of technical unplanned costs. An interesting fact to note is that the variation in vessel operation hours does not affect unplanned costs in a similar manner.

For FSM and for Case 2, it is also noted that financial costs represent nearly the same proportion as technical unplanned costs. Because a huge part of these unplanned costs incur in a distant future, the inflation accounted for these costs is relatively high. This results in a significant increase in financial costs. In summary, it is shown that technical unplanned costs can vary significantly, depending on the operational countries and the length of the contract duration.

One other factor included in the technical unplanned cost is an insurance premium. As previously described in the section "Methodology," unplanned maintenance costs are divided into failure costs above and below a threshold value. An insurance will cover the costs above a threshold value for a maximum number of six failure events per year. For BSM, an insurance premium is paid annually by vessel operators, or for FSM, this premium is by the engine manufacturers. In the following paragraph, we refer to "threshold" as limit of the monetary value of the failure events, and "barrier" as limit of the number of failure events occurring in a year.

In order to understand the influence of an insurance premium on the costs of FSM, we perform an analysis on technical unplanned costs. The unique feature of our proposed methodology is the enhancement of the methodology known in engineering-oriented LCC literature with finance and risk management methodologies. Thus, it enables us to study technical and financial aspects of our contract types. Such an analysis cannot be actively considered in models based solely on engineering-oriented LCC literature.

For instance, a model that builds exclusively on engineering-oriented literature would probably include insurance as a fixed cost. Our methodology allows us to consider that insurance is in effect not a fixed cost, but a relevant integral part of the contracts. Such an insurance cost is flexible and could be optimized with the help of the tool.

We present this finding through the results of our analysis for Case 3. Even though we only show results for Case 3, it should be noted that a similar analysis can be performed for FSM of Cases 1 and 2. The analysis results for Case 3 are shown in Figure 4. We observe that a large share of the costs of FSM is due to the insurance premium, while the total failure costs above the threshold play a minor role (less than 5 percent).

Notes: Technical unplanned without insurance includes labor and spare part costs below the insurance threshold value – these costs are borne by the engine manufacturer. Technical unplanned with insurance (colored in solid black) is less than 5 percent of total FSM costs. Technical unplanned with insurance is the unplanned maintenance costs above the insurance threshold value, within six failure events per year and is paid by the insurance company

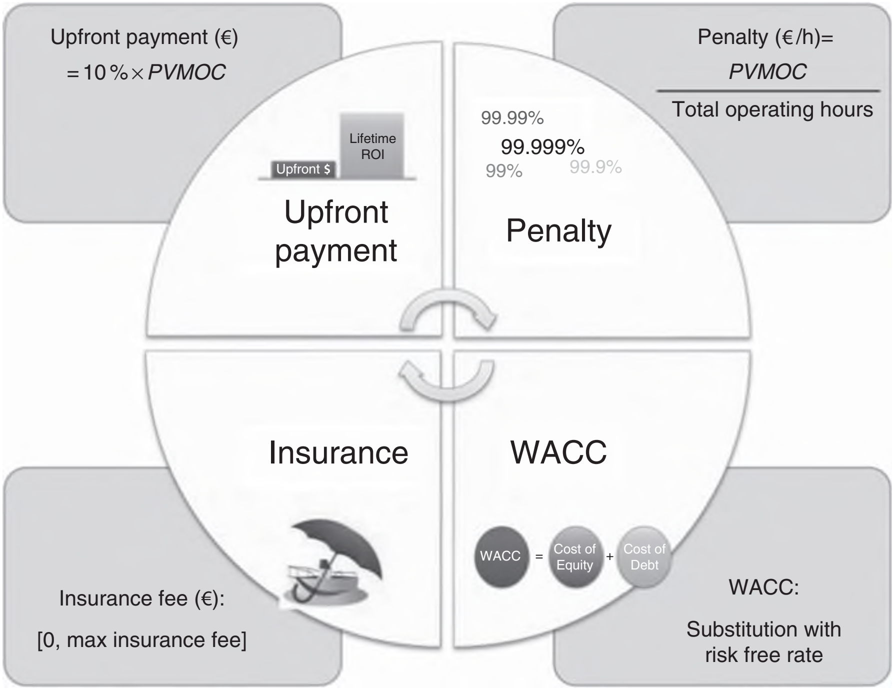
Figure 4.
The pie chart shows the influence of insurance on the costs of full service maintenance (FSM) calculated for Case 3

The small amount of technical unplanned costs is due to fact that the underlying probability distribution returns only a low probability for the occurrence of the number of failure events above the threshold and an even lower probability of failure events above the barrier. The probability distribution is associated with potential failure events and based on empirical data. Therefore, failure costs above the threshold, which are compensated by the insurance, are small in comparison to the cost of the insurance premium.

As a side note, this can be used as an indication that the engines are reliable and there is a potential to optimize the costs of FSM through reduction of insurance premium costs. To further investigate the influence of the insurance premium on costs, we completely exclude insurance from our LCC calculation. The results show a decrease of 20 percent in the NPV of all expected future costs for FSM. Moreover, the resulting NPV is considerably below the NPV of the costs associated with insurance. Nevertheless, in this case, one must point out that all failure costs must paid by the engine manufacturers, which can be substantial for non-reliable engines.

Therefore, it seems to be questionable whether inclusion of insurance with these conditions in FSM is economically reasonable at all. In our case study, we also vary the insurance premium and compare the resulting NPV of all expected future costs to the instance without insurance. It has to be remarked that the intersection between these two functions results in an extraordinary low insurance premium in comparison to the engine purchase price. Thus, the total costs of a higher insurance premium will exceed the expected total costs of failure events exceeding the threshold and the barrier. The results of this analysis also indicate that for FSM, insurance should be taken with a careful consideration to its conditions, i.e., insurance premium, threshold and barrier. We also further investigate the effects of important financial parameters such as upfront payment, penalty and WACC on the total maintenance costs for both BSM and FSM. These three parameters are shown together with the insurance premium in Figure 5. Our study shows that an upfront payment for a long contract duration will reduce financial risk and subsequently maintenance costs. Further, high engine reliability and long TBO result in low penalty costs, and subsequently a small influence on the total costs for BSM and FSM.

As interest rate varies with operational country, this can also significantly affect the total maintenance costs. The combined factors of both contract duration and economic stability



Note: PVMOC is defined as the present value of engine maintenance (operational) costs for the contract duration

Figure 5. Variable financial parameters investigated in the sensitivity analysis for full service maintenance contract

in the operational country can result in a variation in the interest rate that subsequently affects the total costs. Nevertheless, any international operating companies are exposed to such risks due to their worldwide sales, and these risks can be considered accordingly through a careful financial evaluation.

With regard to LS, the determinants of the engine's operational and maintenance costs stay the same and are consequently not specifically inspected. Our major interests are the market value of the engine as well as the credit risk. For the former, we show that the market value is only a minor driver of the leasing fee. This coincides with the results of our literature review, in which the operational costs of the products are dominant.

Regarding credit risk, our results indicate that a lower customer rating (from Standard & Poor's rating "A" to rating "B") results in a 10 percent increase in the minimum fee per engine operating hour. This increase is expected, because a lower customer rating subsequently increases the probability of the default λ, i.e., the customer has a higher probability not to complete the contract and the supplier incurs costs associated with demounting and repossessing the engine.

In summary, we have presented in the first part of this section the tool developed in application of our proposed methodology and accordingly used in our case study. Based on our results, we have also shown that our proposed methodology can be applied to analyze LCC structures for three different contract types and for real-world scenarios. It has also been established that key drivers of the total costs can be differentiated from minor drivers. Finally, we have demonstrated that our proposed methodology utilizing a combination of different approaches can lead to satisfactory LCC analysis results.

While the proposed methodology and analysis presented in this paper mainly focuses on the suppliers' point of view, we would like to emphasize that such a methodology will be beneficial to customers too. As mentioned in the introduction, product purchases in B2B markets are greatly influenced by both, the initial capital expenditures and the expected operational costs occurring over product's lifetime. Therefore, customers have a great interest in a thorough evaluation of the products LCC.

Considering the mentioned assumptions, our methodology and tool allow customers to estimate LCC of various B2B products and thus to understand commercial risks and benefits, upon which a thorough decision can be based upon. This enables a realistic and rather equivalent comparison of LCC costs of similar products from different suppliers. For example, an LCC for similar products can vary dramatically when one supplier includes only cost of spare parts without accounting for logistic risk, while the other includes the risk.

Moreover, the usage of such a tool will prevent future discrepancy between customers and suppliers regarding the estimation of the product's LCC. This can lead to disappointment when future service and maintenance costs are higher than previously estimated during the purchasing phase. As such, the tool will enable a higher transparency regarding the LCC for the supplier and customer. Hence, it helps to establish and maintain sustainable long-term relationships, which benefits both, the suppliers and customers.

In addition to that it should be noted that inherent to any products is possibility of products failures beyond of their warranty period. However, this should be minimized with proper intensive products testing and validation which are the B2B industry standard. To cover this risk, extra warranty can be offered by suppliers for possible costs of occurring unplanned maintenance service – calculated in the methodology as unplanned maintenance costs.

Conclusion and future work

In this paper, we develop a methodology and implemented the latter into a tool to estimate the LCC for complex B2B products that incorporates methods from engineering statistics and economics as well as methods from finance.

The specific challenges for an accurate LCC estimation of such products are as follows:

- quantifying the planned and unplanned downtime of highly complex products (with some thousands of subsystems and possible sources of defects);
- the integration of logistical aspects based on geographical operational locations of the products, the integration of the fact that produces can move from one location to another during their respective lifetimes;
- the integration of financial and especially country risks;
- the option to insure against unplanned maintenance costs; and
- the consideration of credit risk in case of leasing.

These challenges prevent the usage of standard frameworks to estimate the LCC. The presented methodology takes into consideration different types of risks, both technical as well as financial.

The proposed method is implemented for three types of contracts, mainly:

(1) a deterministic BSM with only planned maintenance;

(2) a non-deterministic FSM with planned and unplanned maintenance and repairs; and

(3) a leasing contract (LS).

Based on the results of our case study, we show the practicability and effectiveness of our interdisciplinary methodology in analyzing the LCC structures of large diesel engines from real industry cases. The results also highlight the interplay of technical as well as financial risks. Here case in point, the higher interest rate inherent in country risk significantly influences the LCC. On the other hand, technical risk can be transferred to an insurer. However, its influence on the LCC is mainly driven by the insurance premium paid. Finally, factors such as high reliability, long TBO and extensive worldwide after-sales coverage prove to be important factors in reducing significantly risks and costs. The methodology used in this study can certainly be transferred to other industries such as airplanes or power stations which is of special interest for the practice of engineering management.

We see future research in three directions. First, in academic literature, we identified a research gap especially in case of the influence of logistics in maintenance management. Here the influence of different national logistic networks should be analyzed with regard to the influence of the LCC. Second, while multiple risk considerations are included in our approach, additional uncertainty management provisions – e.g. if not all listed assumptions (e.g. availability of empirical MTBF data) – are needed in future research. Third, for the practice of engineering management, there is room for expanding the presented methodology to other application field like airplanes or power generation.

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Corresponding author
Andreas Rathgeber can be contacted at: andreas.rathgeber@mrm.uni-augsburg.de