9th International Conference on Through-life Engineering Service
3-4 November 2020, Cranfield UK

A Super Simple Life-cycle Cost Estimation Model with Minimum Data Requirement

Maryam Farsi[a]*, John Ahmet Erkoyuncu[a], Andrew Harrison[b]

[a] *Through-life Engineering Services Centre, Cranfield University, Cranfield, MK43 0AL, UK*
[b] *Rolls-Royce Plc, PO Box 31, Derby, DE24 8BJ, UK*

* Corresponding author. Tel.: +44-123-475-0111. *E-mail address:* maryam.farsi@cranfield.ac.uk

Abstract

Life-cycle costing is a practical approach to estimate the total cost of ownership in product-service systems. In high-value manufacturing sectors, due to the complication of overhaul invoices, shop visits, repair and maintenance interventions, identifying service cost reduction opportunities can be complex. Moreover, quantifying the impact of key cost drivers on the total cost is challenging due to the lack of complete historical data and high level of uncertainties within the service cost data. To address these challenges, a super simple life-cycle cost model architecture is presented. A set of minimum data requirements is identified for the development of the presented cost model. The model architecture comprises of life-cycle cost breakdown structure and work breakdown structure to specify the cost drivers, unit costs and their frequencies. A bottom-up activity-based cost estimation approach is implemented to calculate the total life-cycle cost of a product. The way that the minimum data requirement is applied to the cost estimation structure is explained. In addition, the minimum data is employed to perform a deterministic sensitivity analysis to compare the relative impact of the model input on the total cost. The Monte-Carlo simulation is performed for estimating the uncertainty propagation on the total life-cycle cost. The presented model architecture simplifies life-cycle cost estimations and service control decisions for maintenance, repair, and overhaul actions. A case study of life-cycle cost estimation in the machine tool industry is considered for testing the validity of the cost model architecture.

Keywords: Life-cycle Costing; Maintenance, Repair and Overhaul; Activity-based Cost Estimation; Uncertainty Analysis; Sensitivity Analysis; Monte Carlo

1. Introduction

Product life-cycle cost (LCC) is the sum of the estimated costs in the span of acquire to disposal phases of a product or a major asset/equipment (i.e. parent) and all the sub-assemblies (i.e. child). LCC analysis and estimation have been studied by several authors in the past few decades. The subject has been discussed within different contexts such as Product Life-cycle Management (PLM) [1,2], reliability [3], cost of ownership [4], cost engineering [5,6] and servitization [7–9]. LCC is known as an effective approach to estimate the total cost of ownership (ownership cost) [4]. Moreover, the concept of cost engineering has emerged to improve product designs and reduce the cost of design [10]. According to literature, the main LCC phases are design, production, operation, and disposal [4,10,11]. Each cost element includes a set of key cost events that has a significant influence on LCC and the selection of cost-effective equipment and processes for the lowest long-term cost of ownership. In the context of business operations, the top-level life-cycle cost breakdown includes the cost of capital expenditure (CapEx) and operating expenditure expenses (OpEx). CapEx and OpEx entail the direct and indirect costs for acquiring and sustaining a major asset. However, excising literature mostly emphasizes on a statement that LCC breakdown cannot be generalized, and it depends on the specific major asset [3].

Since the 19th century, several LCC frameworks have been developed in the areas of manufacturing, aerospace, construction, energy, and transportation with a view to proposing life-cycle costing processes and estimations [1,4,12–14]. The cost estimation approaches can be categorized into traditional, conceptual, analytical and heuristic. Traditional cost estimation mainly relies on the experience of the estimator [15,16]. Conceptual models are based on a set of hypotheses which are expressed in the form of qualitative frameworks at the product level. Despite their flexibility and generic form, the conceptual approaches are unable to quantify LCC. Some of the qualitative techniques are intuitive and analogical techniques [17]. Analytical models are based on mathematical formulations with respect to certain conditions and assumptions to calculate LCC. Similarly, Heuristic models are partly based on mathematical theories and analytical models. However, these methods do not guarantee a solution for LCC. Parametric models are also based on mathematical and statistical methodologies when the parameters necessary to estimate the cost are known, and their mathematical relationships are formulated [10,17]. Featured based costing is a parametric approach which heavily relies on CAD/CAM technologies to estimate the cost based on features of a part (i.e. edges, hole, folds etc.) [5]. Activity-based cost (ABC) estimation is one of the analytical approaches where LCC can be estimated as the sum of the costs of activities associated to the life-cycle. This method was initially proposed by Cooper and Kaplan [18]. ABC as a bottom-up analytical approach, can provide a more accurate calculation compared to the traditional estimation techniques and other analytical approaches. The advantages and capabilities of ABC have been discussed in the literature by [19–25]. In addition to the importance of life-cycle cost estimation methodologies, the significance of uncertainty analysis on cost estimations and its influence on robustness and reliability of the cost related decisions are highlighted in [26,27].

In high-value manufacturing with a high level of uncertainty, due to the lack of complete historical data on the service costs and complication of repair and maintenance planning, implementing a bottom-up LCC approach can simplify the process of LCC estimations. Furthermore, it supports decision-makers to identify service cost reduction opportunities. However, one of the main criticisms to the bottom-up cost estimation approaches has been always the complexity of cost calculations and the need for too many requirements. To address these challenges and move towards a simpler approach for ABC, in this paper, the authors have proposed a super simple life-cycle cost model architecture which can be applied for major assets irrespective of the industry and the major equipment type. Moreover, a set of minimum data requirements is identified to estimate LCC. The model architecture comprises of life-cycle cost breakdown structure (CBS) and work breakdown structure (WBS) to specify the cost drivers, unit costs and their frequencies. Additionally, to assess uncertainty, a three-point estimation approach for ABC is considered. The uncertainty and sensitivity analysis are conducted using a static Monte-Carlo technique in Excel.

The structure of the paper is as follows: the literature on life-cycle cost models, estimation techniques and uncertainty analysis for cost models are reviewed in Section 2. The proposed architecture of the cost estimation model is presented in Section 3. Section 4 presents the adopted case study for testing the cost model. Section 5 provides a discussion on the model implementation. The concluding remarks and future work are presented in Section 6.

2. Literature Review

In the past 5 decades, several models and approaches for life-cycle cost estimation and procedures have been studied, proposed and discussed. However, the complete deployment and application of such models are still a challenging task for many businesses. In the late 19th century, Barringer, et al. [3] and Woodward [4] proposed an LCC framework in which the cost estimation process starts with problem definition and continues with the selection of service support alternatives, cost breakdown preparation, selection of analytical cost model, cost estimation, cost profile preparation, break-even chart, Pareto analysis, sensitivity analysis, risk assessment, and finally by selecting the preferred course of actions. Woodward also presented critical cost parameters for the LCC estimation that are Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), the time period between overhauls, time period for scheduled maintenance, and energy use rate [4]. In two different studies, Zhao, et al. [11] and Gransberg [28] presented the other key parameters for LCC estimation as major equipment life, and its economic life. Cheung et al. [13] developed a unit cost modelling methodology to allow engineers to understand CBS. The methodology was applied to a Rolls-Royce aero-engine fan blade to conduct a design optimization. Xu et al. [2] introduced a product LCC framework to support decision making at the early stages of PLM. The framework was developed based on ABC and dynamic object-oriented modelling and programming. Asiedu and Gu [10] argued that the concept of PLM, together with cost engineering approaches, has resulted in the concept of design for 'X' realm - e.g. design for manufacturability, design for assembly, design for producibility, design for maintainability, and design for quality.

Different LCC estimation approaches and methodologies are discussed in the literature solely focusing on certain phases of product life-cycle. For instance, Shehab and Abdalla [29] presented a knowledge-based fuzzy system for product cost modelling in the design and development phase. Castagne, et al. [30] expanded the work of Shehab and Abdalla [29] by proposing a hierarchical model to estimate the LCC of an aircraft frame. Laxman et al. [31] illustrated a detailed LCC estimation for repairable systems using calculations in relation to reliability and maintainability aspects. The focus of their research was on maintenance and repair costs using stochastic point processes. Zhao et al. [11] proposed a component deterioration-driven cost estimation framework for an engine life-cycle. They focused on the product operation and support, and disposal phases of the life-cycle. Fioriti, et al. [32]

presented a component (i.e. engine) level methodology to estimate the cost of maintenance for civil aircrafts. Their model quantifies the effect of the aircraft's individual components on the total maintenance cost using linear regression method.

Haroun [25] developed a generic procedure for calculating the cost of maintenance jobs to a reasonable degree of accuracy using the ABC approach. He concluded that the application of ABC leads to a more accurate estimation for maintenance costs. Moreover, ABC is more flexible in terms of updating the algorithm input. This approach provides more flexibility to control the maintenance activities and therefore enhances the reliability in the service decision-making. In a more recent study, Duran and Afonso [33] expanded the implementation of LCC and proposed an ABC model for the management of non-repairable spare parts. Their approach used Weibull distributions to define the reliability of spare parts with a view to support the service strategies and inventory policies.

Uncertainty in LCC estimations has been widely studied, and different types of uncertainties in LCC are identified. Moreover, the processes and strategies to effectively deal with the uncertainties are examined [6,7,34,35]. A general approach for the estimation of LCC distributions at both the product and component levels is presented by Fleischer et al. [36]. Their proposed approach provided the basis for assessing the risks in contract costing using the Monte-Carlo simulation. The benefits of considering and implementing uncertainty tools, models and simulations in maintenance and service decisions are analyzed by Erkoyuncu, et.al [37]. Later, the authors in [34] presented an overview of metrics which can be used for uncertainty analysis in cost estimation. Considering the importance of uncertainty in decision-making, Florian, et al. [38] developed a holistic LCC approach for cost management in product development. Their proposed approach supports decision-makers through optimization and trade-off analysis of capital and operational cost drivers based on LCC modelling.

3. The Super Simple LCC Estimation Model

A super simple architecture for LCC estimation has been developed based on the literature and the theoretical aspects of LCC models and estimation approaches presented in Section 2. The proposed cost model architecture is therefore developed as the IDEF0 diagram as presented in Figure 1. In the cost model architecture, the model inputs are cost and work breakdown structures throughout the life-cycle (Section 3.1), and the minimum data requirements proposed in this study (Section 3.1.1). Activity-based costing approach, Monte-Carlo simulation with triangular distribution, and sensitivity analysis based on three-point estimation method are selected for the model mechanisms (Section 3.2). The outputs are the life-cycle cost breakdown, and the outcomes from the sensitivity and uncertainty analysis (Section 4.2). Different elements of the architecture are explained in this Section. The model requirements in terms of the critical input parameters, CBS and WBS are discussed in Section 3.1. The ABC approach for cost estimation is presented in Section 3.2. The proposed cost model includes both the costs a component causes, in addition to those it consumes. Some costs caused by a component may be spent on activities or assets other than the component e.g. penalty charges, loss of revenue, insurance etc. Moreover, the model is structured in line with the key decision points in the cost creation process, allowing the results to be used to focus mitigation action in the areas of most impact.

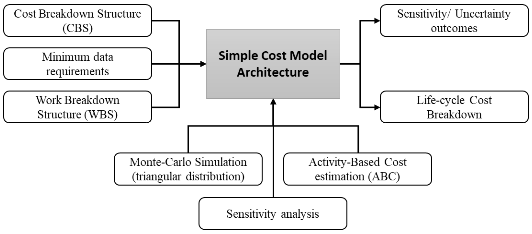

Figure 1: Simple life-cycle cost model architecture

3.1. Model Requirement

In this study, a ***Product***, for which an LCC estimation is developed, can be a complete asset, or an artefact in the assembly or sub-assembly levels. Moreover. ***Life-cycle*** is the expected life-span of the product under consideration. The proposed product life-cycle CBS and the interactions between the cost events are presented in Figure 2.

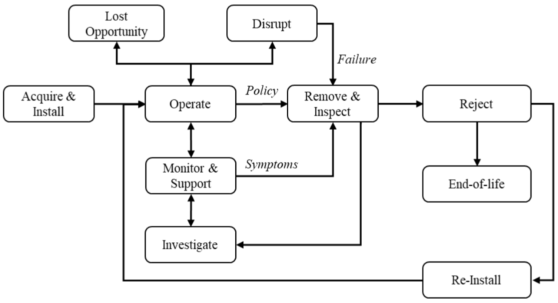

Figure 2: Cost breakdown structure

The cost events are described below:

- ***Acquire & Install*** cost is the cost of design and production of an asset (e.g. engine) or acquisition of a component (e.g. bearing), including the cost of assembly and installation.

- During operation, ***Lost opportunity*** refers to the revenue loss due to the lack of product utilization, availability and credibility.
- ***Disrupt*** is the cost of disruption to the product availability due to a failure in the agreed performance level and capability and according to the terms mentioned within the warrantee and guarantee agreement(s).
- ***Operate*** cost event mainly incorporates the direct cost of operation and consumables (e.g. fuel, gas, water, oil).
- ***Investigate*** refers to the cost of all the investigations and mitigations processes through the product life-cycle.
- ***Monitor & Support*** covers the cost of installed base maintenance (i.e. oil change) and regular monitoring.
- ***Remove & Inspect*** is the cost of taking an item out for inspection.
- ***Reject*** is the cost of repair and replacement.
- ***Re-install*** is the cost of re-assembly and re-installation of a product after removal.
- ***End-of-life*** refers to the product disposal cost and/or revenues if the product has a residual value at the end of life.

For each cost event, the key cost activities (i.e. work breakdown) are summarized in Table 1.

Table 1: Work breakdown structure

Acquire & Install	**Lost opportunity**	**Disrupt**	**Operate**
-acquire -assembly -testing -transport -install	revenue loss due to lack of: -utilization - availability -credibility	penalties due to the lack of: -performance - capability	-consumables
Investigate	**Monitor & Support**	**Remove & Inspect**	**Reject**
-investigations	-base maintenance - routine monitoring	-de-install -dis-assembly - inspect transport	-repair -replace
Re-install	**End-of-life**		
-re-assembly -testing -re-install -transport	- disposal cost - revenue from disposal - un-installation - dis-assembly - transport		

3.1.1. Minimum data requirement

In the previous sections, the life-cycle CBS and WBS for a product are presented. The cost model is then predicated on cost events, and the total life-cycle cost is the summation of the number of cost events and what cost is associated with each event. The proposed minimum requirements and the critical parameters which control the cost incurred during the life-cycle are as follows:

Time Between Overhaul (TBO): is the time between overhaul opportunities for the parent product that contains the child item.

Removal Rate (RR): is the items' inspection rate at each overhaul opportunity; all individual items may not be inspected every time their parent product is overhauled (see Figure 3).

Overhaul Inspection Interval (OII): is the time between inspections of the child item when the parent product is overhauled; this can be therefore calculated as $OII = TBO/RR$.

Rejection rate (Rej): is the probability that the inspected item is rejected (i.e. cannot be used without repair or replacement).

Replace rate (Repl): is the probability that if an item is rejected, it will be replaced (rather than repaired).

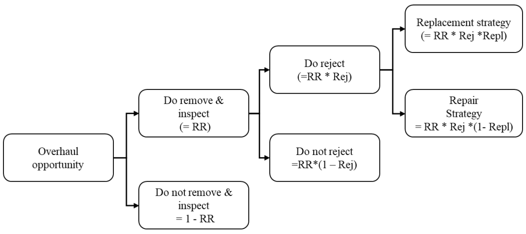

Figure 3: The proposed probability tree diagram at overhaul

Frequency of cost events (f): Given the parameters above, frequencies of some of the LCC cost events are calculated and summarized in Table 2.

Table 2: Frequency of cost events based on critical parameters

Cost event	**Symbol**	**Frequency formula (/year)**
Remove & Inspect	$f_{R\&I}$	$= 1/OII = RR/TBO$
Re-Install	f_{RI}	$= f_{R\&I}$
Reject	f_{Rej}	$= f_{R\&I} \times Rej$
Replacement strategy	f_{Repl}	$= f_{Rej} \times Repl$
Repair strategy	f_{Rep}	$= f_{Rej} - f_{Repl}$ $= f_{Rej} \times (1 - Repl)$

Unit cost or standard cost of events (£): is the unit cost for each cost event (or sum of unit costs of activities at each event) throughout the life-cycle. To capture the uncertainty, the unit costs can be input with a three-point estimation distribution.

3.2. Activity-Base Cost estimation

A simple ABC estimation approach has been implemented to calculate the total LCC as the sum of costs of all the individual event types, as:

$$LCC = \sum_{e=1}^{n} C_e, \tag{1}$$

where, the cost of an event e (C_e) is the cost per event multiply by the number of events, as:

$$C_e = C_e^u \times n_e, \tag{2}$$

where, the cost per event C_e^u , is the sum of costs of all the individual activities in that event, as:

$$: C_e^u = \sum_{a=1}^{m_e} C_{e,a}^u, \tag{3}$$

where, e and a refer to a cost event and an activity in the cost event respectively. n and m_e are the total number of events and the total number of activities in a certain event, respectively. C_e^u is the unit cost of event e and n_e is the total number of events per life-cycle period, as thus:

$$n_e = f_e \times T,$$

where, T is the life-cycle of the product. To include the uncertainty, the values of f_e can be taken with a three-point estimation distribution around the mode value as calculated in Table 2. Moreover, a three-point estimation can be applied to the minimum data requirements i.e. TBO, RR, Rej. and Repl. Which is then propagated through f_e calculations, as shown in Figure 4.

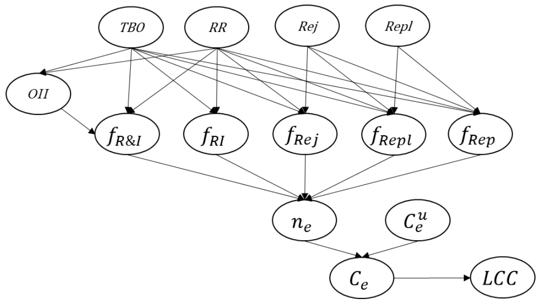

Figure 4: LCC uncertainty propagation network

4. Case study

4.1. LCC results

A case study of a machine tool bespoke service provider in the UK is considered for testing the presented cost model. The life-cycle cost data presented in Table 3 are collected through a set of workshops and interviews with the experts in the company. The following assumptions are made:

- The life-cycle of the machine is assumed as T=30 years.
- The TBO is equal to the MTBF for the machine tool.
- The LCC is estimated for the parent product (i.e. machine tool) and therefore, *RR=1*, and *Rej*=1.
- The repair and replacement strategies have the same probabilities, and thus *Repl* is 0.5.
- The number of scheduled maintenance and the machine failure rate are constant over the life-cycle.

From the case study, the life-cycle cost activities are listed in Table 3. Then, the activities are categorized into the proposed cost events. The unit costs and the frequencies for each cost activity are summarized in Table 3.

Table 3: Case study – life-cycle unit costs and frequencies of each activity

Life-cycle cost phases	**Cost activities**	**Unit cost (£K)**	**Frequency (/year)**
Acquire & Install	Purchase price	£348.00	1/30
	Legal fee	£1.60	1/30
	Dis-assembly	£2.00	1/30
	Transport	£2.00	1/30
	Assembly	£16.00	1/30
	Specification	£4.00	1/30
	Installation	£0.80	1/30
	Testing	£16.00	1/30
	Integration	£16.00	1/30
Lost Opportunity	Penalty	£0.55	1.00
Operate	Operator	£1.35	1/30
Investigation	Investigation	£1.50	2.00
Monitor & Support	Baseline maintenance	£3.75	1.00
	Standby support	£0.50	12.00
Remove & Inspect	Remove and Inspect	£0.48	12.00
Reject	Preventive maintenance	£1.19	2.00
	Corrective maintenance	£0.71	10.00
	Spare part disposal	£5.00	6.00
	Spare part	£15.00	6.00
Re-Install	Re-install	£0.48	12.00
End-of-life	Uninstallation	£2.50	1/30
	Dis-assembly	£2.50	1/30
	Transport	£0.50	1/30
	Retrofit	£50.00	1/30

The input parameters required to calculate the event frequencies from Table 2 are shown in Table 4. and lead to the calculated event frequencies in

Table 5. It also displays the individual activity costs which contribute to each cost event.

Table 4: Case study - critical parameters

Parameter	*TBO* (years)	*RR*	*OII* (years)	*Rej*	*Repl*
Value	0.1	1	0.1	1	0.5

Table 5:Case study – life-cycle unit costs and frequencies of each event

Life-cycle cost phases	**Unit cost of event (K£)**	**Proposed Frequency (/year)**	**Proposed total cost**
Acquire & Install	£406.40	0.03	£13.55
Lost Opportunity	£0.55	1.00	£0.55
Operate	£1.35	0.03	£0.05
Investigation	£1.50	2.00	£3.00
Monitor &	£3.75	1.00	£3.75
Support	£0.50	12.00	£6.00
Remove & Inspect	£0.48	10.00	£4.75
Reject	£1.90	10.00	£19.00
	(spares disposal) £20.00	5.00	£100.00
Re-Install	£0.48	10.00	£4.75
End-of-life	£55.50	0.03	£1.85

The unit cost of each activity is the cost per year, not the total cost over the life span. The cost of each activity is, therefore calculated by multiplying the unit costs and the frequencies. Utilizing the proposed approach, the unit cost of each life-cycle event (Equation (1)) and their frequencies (see Table 4) are calculated as presented in Table 5. The cumulative total cost of LCC over the 30 year period is therefore calculated as £4.72m.

4.2. Sensitivity and Uncertainty Analysis

A deterministic sensitivity analysis with the sensitivity variation of 5% is carried out to compare the relative impact of the individual cost of events on the total LCC. All the model inputs were varied around their nominal values by ±5% (both event timing and event cost inputs). For simplicity, the ± 5% variation was applied to the cost of an event (the sum of contributing activity costs) rather than the individual contributing activity costs themselves. A tornado diagram was created in Excel, and the results are presented in Figure 5. The tornado diagram shows the sensitivity of the cost of events C_e to the ±5% changes in the selected variables.

Moreover, the relative impact of the ±5% sensitivity change on different LCC events are presented in Figure 6. The charts show the total 30-year cost impact from each input change.

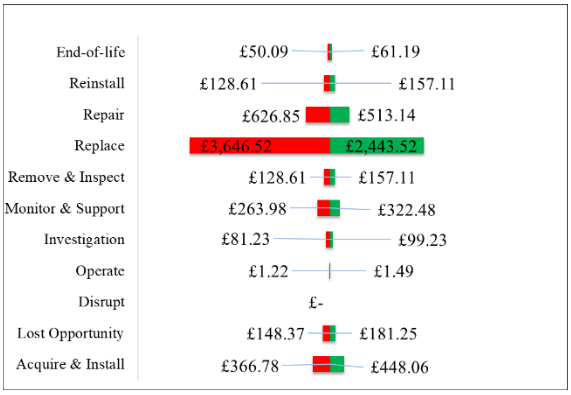

Figure 5: Sensitivity analysis results (costs are in £K)

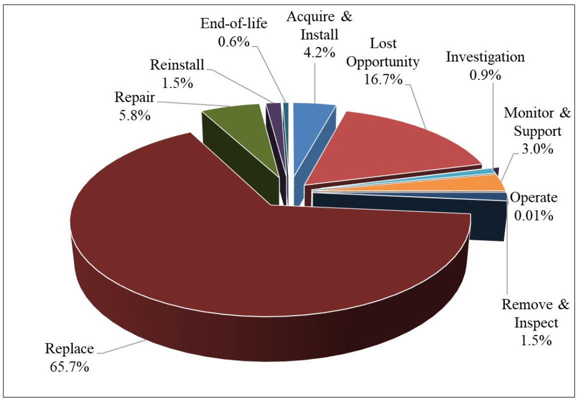

Figure 6: 5% Sensitivity impact on life-cycle cost events over 30 years

Furthermore, an uncertainty analysis using the Monte-Carlo simulation was carried out in Excel to quantify the aggregate uncertainty of total LCC over the 30-year period. A constant sensitivity variation of ±5% is applied as the three-point estimation of (mode value ± 5%), to all the cost inputs and the frequencies. The aggregate uncertainty is then calculated and plotted as a histogram of the probability density function (PDF) as presented in Figure 7. Following the application of three-point-estimation, the results show a triangular distribution as expected.

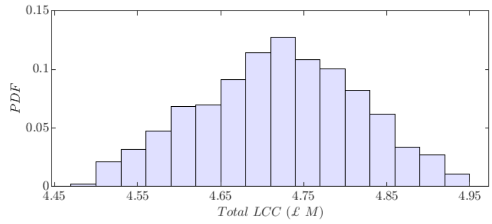

Figure 7: Monte-Carlo simulation results (costs are in £K)

5. Discussion

In this study, the LCC of a machine tool is calculated based on the cumulative cost of events and the proposed simple ABC approach using minimum data requirements. Utilizing the proposed approach, the frequencies of 'remove & inspect' and 're-install' can be calculated based on the TBO or MTBF. Thereby, the approach assumed that the scheduled tasks for regular preventive interventions should be completed at the time that the product is at the overhaul/workshop for unscheduled corrective maintenance. In this case study, ignoring this strategy leads into a 7.31% over-costing in the total LCC, which is not ideal. The proposed approach eliminates such over-costing and simplifies the LCC estimation by minimizing the number of inputs for LCC event frequencies to four main parameters of time between overhaul (or MTBF), removal rate, rejection rate and replace rate.

The LCC results of the case study using the proposed approach are presented in Table 5. Assuming 30 years as the life-cycle, the machine operation and maintenance cost is 91% of the total LCC. The Acquire costs in year-one and the disposal cost at year 30 are only 8% and 1% of the LCC respectively.

According to the uncertainty propagation network in Figure 4, the aggregate uncertainty in LCC arises from the uncertainties in costs and frequencies of life-cycle events. The frequencies are more critical to explore in the sensitivity and uncertainty analyses, as they are a cascade of earlier events in the sequence such as *TBO, RR, Rej. and Repl.* Figure 4 shows that *TBO* has the most impact on the total cost. Sensitivity analysis shows a 5% variation in this input yielding a 21% variation in total LCC. This 21% variation mostly influences Reject-Replace strategy, with 14% (=21%*65.7) discrepancy.

6. Concluding remarks

A simple generic product life-cycle cost model architecture using a set of minimum requirements is proposed. The proposed model architecture (see Figure 1) utilizes the minimum requirement (see Section 3.1.1) and the product cost-breakdown structure and work-breakdown structure to estimate the LCC using the activity-based costing approach. The proposed approach is generic and can calculate LCC for a product at asset, assembly and sub-assembly levels. The developed model has been illustrated through a specific application for a machine tool case study. The comparison between a complete CBA and the proposed approach shows a variation of 7.31% as discussed in Section 5. Moreover, the integration of sensitivity and uncertainty analyses are demonstrated using the case study. Based on the analysis carried out on the case study, the following conclusions are drawn:

- The life-cycle operation and maintenance costs dominated the machine tool life cycle cost.
- The sensitivity in total life-cycle cost is mostly influenced by the time between overhaul (or MTBF)
- The sensitivity in cost data mostly influences the replacement cost.

The presented model architecture simplifies LCC estimations, since it requires fewer data to estimate the cost. Moreover, the impact of service costs on LCC from different support decisions for repairable and non-repairable items (i.e. Table 4) can be analyzed.

The further work would be focused on capturing the dynamic interactions between cost events and quantifying the aggregate uncertainty stochastically using an object-oriented approach.

Acknowledgements

This research is supported by the Innovate UK [Grant No. 103082-263289] and Through-life Engineering Services Centre at Cranfield University.

References

[1] Rink DR, Swan JE. Product life cycle research: A literature review. J Bus Res 1979;7:219–42. doi:10.1016/0148-2963(79)90030-4.

[2] Xu X, Chen JLQ, Xie SQ. Framework of a product lifecycle costing system. J Comput Inf Sci Eng 2006;6:69–77. doi:10.1115/1.2161227.

[3] H. Paul Barringer, P.E., Barringer & Associates I. Life Cycle Cost & Reliability for Process Equipment. In: American Petroleum Institute, editor. 8th Annu. Energy Week Conf. Exhib., Houston, Texas: American Society of Mechanical Engineers & PennWell Publishing; 1997, p. 1–22.

[4] Woodward DG. Life cycle costing - Theory, information acquisition and application. Int J Proj Manag 1997;15:335–44. doi:10.1016/S0263-7863(96)00089-0.

[5] Rush C, Roy R. Analysis of cost estimating processes used within a concurrent engineering environment throughout a product life cycle. 7th ISPE Int Conf Concurr Eng Res Appl 2000;44:58–67.

[6] Xu Y, Elgh F, Erkoyuncu JA, Bankole O, Goh Y, Cheung WM, et al. Cost Engineering for manufacturing: Current and future research. Int J Comput Integr Manuf 2012;25:300–14.

[7] Erkoyuncu JA, Roy R, Shehab E, Wardle P. Uncertainty challenges in service cost estimation for product-service systems in the aerospace and defence industries. Proc. 19th CIRP Des. Conf. Des., Cranfield Pres: 2009.

[8] Harrison A. Service Knowledge Management for Product Service Systems – a systems design approach –. Funct. Think. Value Creat., Springer Berlin Heidelberg; 2011, p. 12–12. doi:10.1007/978-3-642-19689-8_3.

[9] Zhao X, Verhagen WJC, Curran R. Estimation of aircraft component production cost using knowledge

based engineering techniques. Adv Eng Informatics 2015;29:616–32. doi:10.1016/j.aei.2015.05.004.

[10] Asiedu Y, Gu P. Product life cycle cost analysis: State of the art review. Int J Prod Res 1998;36:883–908. doi:10.1080/002075498193444.

[11] Zhao Y, Harrison A, Roy R, Mehnen J. Aircraft Engine Component Deterioration and Life Cycle Cost Estimation. Glocalized Solut. Sustain. Manuf., Springer Berlin Heidelberg; 2011, p. 657–62. doi:10.1007/978-3-642-19692-8_114.

[12] Korpi E, Ala-Risku T. Life cycle costing: A review of published case studies. Manag Audit J 2008;23:240–61. doi:10.1108/02686900810857703.

[13] Cheung JMW, Scanlan JP, Wiseall SS. An aerospace component cost modelling study for value driven design. In: Cranfield University Press, editor. Proc. 19th CIRP Des. Conf. Des., Cranfield, UK: 2009.

[14] Nissen A. LCC-analysis for switches and crossings: A case study from the Swedish railway network. Int J COMADEM 2009;12:10–9.

[15] Rush C, Roy R. Expert judgement in cost estimating: Modelling the reasoning process. Concurr Eng Res Appl 2001;9:271–85. doi:10.1177/1063293x0100900404.

[16] Daneshkhah A, Hosseinian-Far A, Sedighi T, Farsi M. Prior Elicitation and Evaluation of Imprecise Judgements for Bayesian Analysis of System Reliability. Strateg. Eng. Cloud Comput. Big Data Anal., vol. 1, Cham: Springer International Publishing; 2017, p. 63–79. doi:10.1007/978-3-319-52491-7_4.

[17] Niazi A, Dai JS, Balabani S, Seneviratne L. Product cost estimation: Technique classification and methodology review. J Manuf Sci Eng Trans ASME 2006;128:563–75. doi:10.1115/1.2137750.

[18] Cooper R, Kaplan RS. How Cost Accounting Systematically Distorts Product Costs. Account Manag F Study Perspect 1987:49–72.

[19] Noreen E. Conditions Under Which Activity-Based Cost Systems Provide Relevant Costs. J Manag Account Res 1991;3:159–68.

[20] Hundal MS. Product costing: A comparison of conventional and activity-based costing methods. J Eng Des 1997;8:91–103. doi:10.1080/09544829708907954.

[21] Kee R, Schmidt C. Comparative analysis of utilizing activity-based costing and the theory of constraints for making product-mix decisions. Int J Prod Econ 2000;63:1–17. doi:10.1016/S0925-5273(99)00005-5.

[22] Spedding TA, Sun GQ. Application of discrete event simulation to the activity based costing of manufacturing systems. Int J Prod Econ 1999;58:289–301. doi:10.1016/S0925-5273(98)00204-7.

[23] Tornberg K, Jämsen M, Paranko J. Activity-based costing and process modeling for cost-conscious product design: A case study in a manufacturing company. Int J Prod Econ 2002;79:75–82. doi:10.1016/S0925-5273(00)00179-1.

[24] Ben-Arieh D, Qian L. Activity-based cost management for design and development stage. Int J Prod Econ 2003;83:169–83. doi:10.1016/S0925-5273(02)00323-7.

[25] Haroun AE. Maintenance cost estimation: Application of activity-based costing as a fair estimate method. J Qual Maint Eng 2015;21:258–70. doi:10.1108/JQME-04-2015-0015.

[26] Daneshkhah A, Hosseinian-Far A, Chatrabgoun O, Sedighi T, Farsi M. Probabilistic Modeling of Financial Uncertainties. Int J Organ Collect Intell 2018;8:1–11. doi:10.4018/IJOCI.2018040101.

[27] Farsi M, Grenyer A, Sachidananda M, Sceral M, Mcvey S, Erkoyuncu J, et al. Conceptualising the impact of information asymmetry on through-life cost: case study of machine tools sector. Procedia Manuf 2018;16:99–106. doi:10.1016/j.promfg.2018.10.172.

[28] Gransberg DD, Investigator P. Major Equipment Life-cycle Cost Analysis 2015.

[29] Shehab E, Abdalla H. An intelligent knowledge-based system for product cost modelling. Int J Adv Manuf Technol 2002;19:49–65. doi:10.1007/PL00003967.

[30] Castagne S, Curran R, Rothwell A, Price M, Benard E, Raghunathan S. A generic tool for cost estimating in aircraft design. Res Eng Des 2008;18:149–62. doi:10.1007/s00163-007-0042-x.

[31] Waghmode LY, Sahasrabudhe AD. Modelling maintenance and repair costs using stochastic point processes for life cycle costing of repairable systems. Int J Comput Integr Manuf 2012;25:353–67. doi:10.1080/0951192X.2010.551783.

[32] Fioriti M, Vercella V, Viola N. Cost-estimating model for aircraft maintenance. J Aircr 2018;55:1564–75. doi:10.2514/1.C034664.

[33] Duran O, Afonso PSLP. An activity based costing decision model for life cycle economic assessment in spare parts logistic management. Int J Prod Econ 2020;222. doi:10.1016/j.ijpe.2019.09.020.

[34] Schwabe O, Shehab E, Erkoyuncu J. Uncertainty quantification metrics for whole product life cycle cost estimates in aerospace innovation. Prog Aerosp Sci 2015;77:1–24. doi:10.1016/j.paerosci.2015.06.002.

[35] Goh YM, Newnes L, McMahon C, Mileham A, Paredis CJJ. A framework for considering uncertainty in quantitative Life Cycle Cost estimation. Proc ASME Des Eng Tech Conf 2009;8:3–13. doi:10.1115/DETC2009-86385.

[36] Fleischer J, Wawerla M, Niggeschmidt S. Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses. Adv Life Cycle Eng Sustain Manuf Businesses 2007. doi:10.1007/978-1-84628-935-4.

[37] Erkoyuncu JA, Durugbo C, Shehab E, Roy R, Parker R, Gath A, et al. Uncertainty driven service cost estimation for decision support at the bidding stage. Int J Prod Res 2013;51:5771–88. doi:10.1080/00207543.2013.794318.

[38] Johannknecht F, Gatzen M, Lachmayer R. Systematic approach to optimize cost drivers based on life cycle cost modeling. Proc Int Conf Eng Des ICED 2017;5:121–30.

2020-10-26

A super simple life-cycle cost estimation model with minimum data requirement

Farsi, Maryam

Elsevier

Farsi M, Erkoyuncu JA, Harrison A. (2020) A super simple life-cycle cost estimation model with minimum data requirement. In: TESConf 2020 - 9th International Conference on Through-life Engineering Services, 3-4 November 2020, Virtual Event: Host: Cranfield University

https://doi.org/10.2139/ssrn.3718042