



Towards sustainable manufacturing by enabling optimum selection of life extension strategy for industrial equipment based on cost modelling

Nasser Amaitik¹ · Ming Zhang¹ · Yuchun Xu¹ · Gareth Thomson¹ · Nikolaos Kolokas² · Alexander Maisuradze³ · Michael Peschl³ · Dimitrios Tzovaras²

Received: 31 December 2022 / Accepted: 14 August 2023 / Published online: 5 September 2023
© Crown 2023

Abstract

Sustainable manufacturing is of great importance in today's world. In manufacturing, keep industrial equipment well-functioning is important because failure of equipment leads to significant financial and production losses. In addition, disposal of such failed equipment is both costly and environmentally unfriendly and does not recover any residual value. This raises the need to adopt methods and means that help extending the life of equipment and reduce waste of material. This paper presents a digital toolkit of cost model to estimate and understand the costs to be incurred when applying life extension strategy for industrial equipment. It is meant to be integrated with other tools and methodologies to enable end-users to perform optimal decision-making regarding which life extension strategy (e.g., remanufacturing, refurbishment, repair) to implement for large industrial equipment that is towards its end-of-life or needs maintenance, taking into account criteria such as cost, machine performance, and energy consumption. The cost model developed integrates a combination of parametric costing and activity-based costing methods to perform cost estimation. It has been implemented in an Excel-based Macro platform. A case study with application scenarios has been conducted to demonstrate the application of the cost model to optimize life extension strategies for industrial equipment. Finally, conclusions on the developed cost model have been reported.

Keywords Circular economy · Remanufacturing · Refurbishment · Life extension · Industrial engineering · Industrial equipment · Cost modelling · Decision making · Maintenance · Asset management · Sustainable manufacturing · Digital manufacturing · Smart manufacturing

✉ Nasser Amaitik
n.amaitik@aston.ac.uk

✉ Yuchun Xu
y.xu16@aston.ac.uk

Extended author information available on the last page of the article

Introduction

Adopting circular economy and sustainable manufacturing approaches can massively contribute towards avoiding the worst impacts of climate change and maintaining our planet livable. As the manufacturing sector accounts for approximately 40% of global GDP, manufacturing companies, more than ever, are becoming increasingly concerned about reconsidering of their manufacturing practices and find solutions in order to remain competitive and sustainable in light of the gradual depletion of natural resources around the globe [1–3].

Applying life extension strategies, such as remanufacturing, refurbishment, repair, etc., to restore industrial equipment and avoid waste to landfill would have a positive impact both economically and environmentally while conserving energy and natural resources [4–6].

Accordingly, there is a substantial challenge to develop a decision support tool that helps optimising the selection of most cost-effective life extension strategy that extend the life of industrial equipment. The cost modelling is a key component of such decision support framework in which it provides estimation to the costs to be incurred when applying particular life extension strategy. Therefore, the principle motivation for this paper is to develop simple and tractable methodology that employs analytical approach with human expertise to estimate and analyse total cost of applying life extension strategy for large industrial equipment and thus support informed decision-making. It is a continuation of the preliminary work presented in [7]. The new approach introduced in this paper has an advantage of enabling end-users to perform comparisons among different scenarios of applying life extension strategies. This includes when applying different strategies to different components in the same machine simultaneously or a single strategy to fix only the failed component. Applying life extension strategy not only to the failed component, but also to the components that are near to failure will help achieve long-term potential savings and minimise downtime of the equipment.

The rest of the paper is organised as follows: “[Review of cost estimation methods](#)” section dedicated to review the existing cost estimation methods used in engineering domain for developing models to estimate the cost of manufacturing/life extension of products. Advantages and disadvantages of these methods are also reported. The cost model development procedure is presented in “[Cost model development](#)” section. Details on cost model requirements, architecture and life extension cost estimation methodology are provided in this section. “[Cost model implementation](#)” section demonstrates the implementation of cost model through a case study of estimating costs for different life extension scenarios applied to industrial equipment (friction welding machine). Results of cost model are also presented. And “[Conclusion](#)” section draws conclusion from this work.

Review of cost estimation methods

Generally, cost estimation can be defined as the process of predicting the amount of money required to accomplish certain project. It involves direct and indirect costs that represent utilities, materials, equipment, labour salaries, etc. In order to build the cost model, certain elements about the project might need to be considered, such as duration of the project, size of the project, scope of the project and how complex the project is [8–10].

In engineering domain, there are several cost estimating methods that can be used for developing models to estimate the cost of manufacturing/life extension of products. These approaches can generally be classified into three basic methods, analogy, parametric and

bottom-up costing, or a combination of them. The selection of appropriate method depends largely on the data availability for conducting the estimate [10–12].

Analogy cost estimation combines both historical data and expert judgment to estimate the costs. It involves searching similar products that have been previously manufactured/remanufactured and comparing the similarities with the product that needs to estimate the cost for. Accordingly, cost data of the past similar cases are used to generate cost estimates for the new product [11, 13, 14]. Case-Based Reasoning (CBR) approach can be used for analogy cost estimating. It typically involves retrieving the most relevant past case(s), reusing the case(s) for solving the problem, revising the proposed solution, and then adopting/retaining the solution into the case repository [15, 16]. Goodall et al. [17], Ficko et al. [18], Qin et al. [19] and Ghazali & Murata [20] are examples of applying CBR approach in predicting manufacturing/remanufacturing costs. Analogy costing approach was also combined with analytic costing approach to estimate cost of manufacturing dies [21].

Parametric cost estimation, also known as statistical modelling, is a quantitative method that uses mathematical equations, referred to as Cost Estimation Relationships (CERs), to determine the costs with key cost driver variables that affect costs. The CERs can range from simple equations to complex relationships involving multiple variables. In general, the CERs can be developed by applying statistical analysis, such as linear regression modelling to relate historical data to the costs need to be estimated. However, if historical data is not available or sufficient, the CERs logic can be determined through expert knowledge in which the causal relationships of cost drivers and the output costs are identified [22–24]. The linear regression modelling is the most widely used approach for parametric cost estimation. Smith and Mason [25] and Cavalieri et al. [26] compared linear regression model with neural networks to examine the performance and ease of cost estimation modelling to develop cost estimating relationships (CERs). Camargo et al. [27] studied the possibilities of applying parametric cost estimation methods in the textile and garment industries. An integrated dynamic life-cycle cost (LCC) model that used parametric costing and nested optimization approach has been introduced by Lawand et al. [28] which considers additive manufacturing for repair/remanufacturing to quantify corresponding costs and benefits. Zhang et al. [29] presented a prediction model based on least squares support vector regression and semi-supervised learning to predict the remanufacturing cost of used parts precisely. The application of parametric costing method at the design phase was examined by Duverlie and Castelain [30] and compared with the CBR method. They concluded that the combination of the two methods, parametric and CBR, is feasible. Another application of parametric costing at the design phase was also introduced by [31] for modelling aircraft manufacturing cost when little technical information is readily available. The case study application of proposed model showed an acceptable level of accuracy.

Activity-based costing (ABC), also called “engineering build up costing” or “ottom-up costing”, is a more granular approach where activities of individual tasks are identified and assigned cost according to the actual consumption by each. The ABC approach has been described by many authors [13, 14, 32]. While the two cost estimation methods described above are largely rely on the availability of historical data and/or expert knowledge, the ABC costing, on the other hand, depends on breaking-down the whole process of manufacturing/remanufacturing into smaller work activities for easier and more precise estimating. Once individual estimates are calculated for each activity, they are added up to generate the overall estimate of the cost. Data needed for ABC can be directly collected from users and other available sources. The ABC can also account for indirect costs more accurately by costing the time and resources spent on each activity in the process. Additionally, it facilitates cost tracking so that detailed cost analysis can be performed to identify the most influential

variables on the overall cost. The ABC costing method has been broadly applied in manufacturing/remufacturing domain. Qian and Ben-Arieh [22] also presented a cost estimation model that links ABC with parametric cost estimations of the design and development phases of machined rotational parts. Ardiansyah et al. [12] also introduced a hybrid approach of parametric cost estimation and ABC to generate the cost information of the whole process from the design stage up to development stage. It has been applied to the development of an electric vehicle prototype. Another integrated parametric cost estimation model with ABC approach has been presented by Susanti et al. [33] to estimate production costs of a Li-ion battery pack for e-motorcycle conversion. Each activity's cost of the production process was put into a parametric cost estimation model to calculate the cost of each activity into the total cost of production. ABC has also been used to analyse economic benefit of remanufacturing and a slat track in aircraft wing [34] and support the selection of optimum End-of-Life (EOL) recovery alternative [35, 36] through developing a cost estimation model based on using detailed recovering process information.

Other algorithmic approaches for cost estimation in manufacturing/life extension domain have been introduced in literature. Object-oriented system engineering (OOSE) approach has also been used to establish a life-cycle cost model architecture and a bottom-up approach was adopted to conduct cost estimation [37–40]. Sabharwal and Garg [41] used the graph theoretic approach to calculate the max and min values of cost effectiveness index in order to evaluate the economic viability of remanufacturing. Zhou et al. [42] developed a fuzzy cost model that requires no detailed information on EOL product. the purpose was to use operation cost to select the optimum disassembly method to separate the valuable parts from the old product and used for reuse or remanufacturing. Qin et al. [43] and Ding et al. [44] presented cost analysis frameworks using big data technologies and optimization Back Propagation (BP) neural network algorithm to implement the cost prediction to help enterprises effectively and precisely predict the cost of remanufacturing processes of engineering machinery. A multivariate stochastic model, called Stochastic Cost of Remanufacturing Model (SCoRM), based on Hybrid Pareto Distribution (HPD), Bernoulli process, and a polynomial cost function has been proposed by Gavidel and Rickli [45] for analysing joint effects of core quality condition, return quantity, and timing on remanufacturing cost under normal and extreme return conditions. Data-driven approach has also been used by Jiang et al. [46] which based on decomposition-integration of remanufacturing process to analyse and predict remanufacturing cost of EOL products. Rassölkin et al. [47] discusses the developments in the recycling of electrical machines with attention were devoted to three types of motors: synchronous reluctance motor, permanent magnet assisted synchronous reluctance motor, and induction motor. They assessed the costs of the recycling and then compared it to the amount of products obtained from the electrical machines. Khalil et al. [48] introduced an integrated-cost optimization maintenance model for industrial equipment taking into consideration the stochastic nature of equipment failures as well as the balance between preventive and corrective maintenance costs. They reported promise improvement in equipment availability and reductions in failure rates. Bengtsson and Kurdve [49] explains how a life cycle cost analysis has been performed on machining equipment with a case study from a Swedish company. The developed model are compared to an empirical model and guidelines to consider operation, maintenance and other aspects are given when designing the equipment.

Further to the literature review provided above, Table 1 presents a summary of the strengths and weaknesses for each of the three methods; analogy, parametric and activity-based costing methods [8, 14, 27].

According to the literature review and comparative summary of cost estimation methods provided above, one cannot have an absolute conclusion on which method should be used

Table 1 Comparative summary for cost estimation methods

Method	Strengths	Weaknesses
Analogy Costing	Somewhat easier/faster to implement than ABC Based on actual past cost cases	Relies on expert opinion in adjusting costs Requires similar past cost cases
Parametric Costing	Easier/faster to implement than the other methods Non-technical expert can apply the method Appropriate to conduct sensitivity analysis	Predictive ability reduces outside its data range Requires historical cost data
Activity-Based Costing	Cause and effect identified and understood Accurate estimate Detailed insight and analysis into cost elements	Requires expert knowledge Requires details of the process/activity

to carry out cost estimation. Therefore, it is recommended to use a combination of cost estimation methods, in which strengths and weaknesses are complementary to each other, with expert knowledge in order to obtain reliable and accurate cost estimation model. The cost estimation methodology presented in this paper addresses this issue by integrating activity-based costing and parametric costing methods with expert knowledge so that fast, accurate and detailed cost estimations can be obtained using minimum amount of data required.

Cost model development

The cost model presented in this paper is built to carry out cost estimation and analysis for selected life extension strategy of industrial equipment. This is done through developing ABC costing model for calculating cost of every life extension strategy. Then, system of equations approach is used to calculate the one-off cost that happens when applying a group of simultaneous life extension strategies in which some common activities are performed among these strategies. The gross and net duration-dependent cost of applying life extension strategy will also be identified. This is important because it will help identify the potential savings when applying a group of strategies simultaneously instead of single application of strategies over different times. When data are not available for a particular life extension strategy, the complete set of data for a life extension strategy can be considered as benchmark and then adjusted by expert to estimate corresponding values of other life extension strategies that lack sufficient data.

Cost model requirements

The expected requirements for cost model development include:

- Estimate and analyse the cost of applying single life extension strategy to industrial equipment.

- Estimate and analyse the cost of applying a group of life extension strategies simultaneously to industrial equipment in order to help users identify the potential cost savings.
- Allow users to specify relevant parameters, such as the machines and key components that are often subject to failure, types of failures, strategies applied to every type of failure/component.
- Identify additional costs that manufacturer may incur due to failure of the component.

The main purpose is to allow the comparison and assist in decision-making concerning which the most suitable and cost-effective life extension strategy is for a given condition of equipment (as illustrated in Fig. 1).

The data and knowledge related to cost modelling were captured from the users. Therefore, a combined method of ABC and parametric costing is adopted to provide accurate results based on cost breakdown structure which allow for analysing the distribution of total cost and comparing different life extension strategies.

Accordingly, the parameters data and inputs/outputs data of cost model have been identified as per the following description.

(a) *Cost Model Data and Knowledge:*

The data and knowledge required to build the cost model are defined below.

- *Machines* \Rightarrow list of machines used by manufacturer.
- *Components* \Rightarrow the components of the machine that the end-user needs to calculate cost for. These were divided into two classes, movable components and static components. Movable components represent the critical components that are movable and more degradable, while static-components represent all other components in the machine that are unmovable and less degradable.
- *Failure Type* \Rightarrow types of possible failures that correspond to every component.
- *Strategies* \Rightarrow life extension strategies that can be applied to every type of failure/component.
- *Parameters Values* \Rightarrow the set of parameters values corresponding to price rates (e.g., labour rate, machine/tool rate, etc.), price of new components, etc.

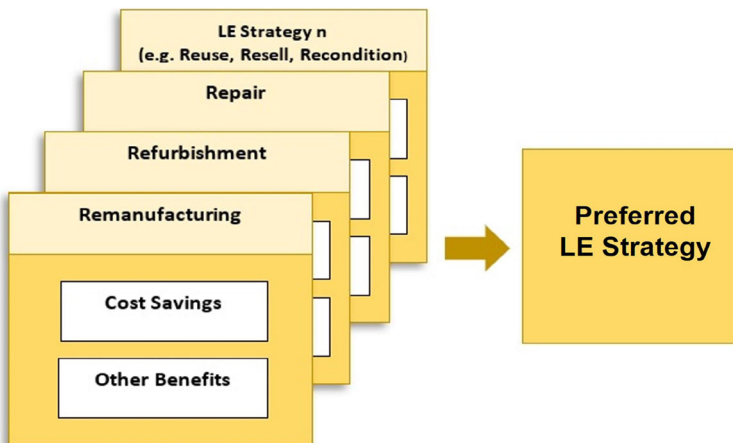


Fig. 1 Comparison of life extension strategies

- *Penalty Costs* \Rightarrow additional cost that will be incurred due to failure of a component. This is called “Penalty Cost due to Failure”. This can be stored into the cost model or entered by the users as input data from the input screen.
- *Resources Consumptions* \Rightarrow the resource consumed (e.g., labour time, machine/tool time, consumables) at each activity that are needed to apply set of life extension strategies simultaneously.

(b) *Inputs to Cost Model:*

The cost model collects inputs from the users in order to perform calculations based on data and knowledge stored in the cost model and returns the cost estimate of applying the strategy and its cost breakdown as outputs. The users can experiment different scenarios of inputs (i.e., combinations of strategies/components) and obtain their corresponding cost outputs. Description of the cost model inputs from the users are given below.

- *Machines Name* \Rightarrow to select the appropriate machine the user wants to analyse.
- *Design Alternative* \Rightarrow to select which set of design alternative data to be considered for cost calculations.
- *Components Name* \Rightarrow to select which component the user wants to analyse.
- *No. of Components* \Rightarrow to specify the number of components to be analysed.
- *Components Failed* \Rightarrow to identify whether a strategy was applied due to component failure or as a maintenance.
- *Failure Type* \Rightarrow to identify the type of failure corresponding to a component.
- *Strategy to be Applied* \Rightarrow to indicate which strategy is going to be applied and calculate cost for.
- *Penalty Cost due to Failure* \Rightarrow to allow users to input additional costs that the pilot will incur due to the failure of the components. If the value is already stored in the cost model, then it will be displayed to the user and have a chance to modify it.

(c) *Outputs of Cost Model:*

The cost output returned by the cost model will be visualised by the users to facilitate cost comparisons between different strategies combinations and give the users insights into the cost contributions for each combination of strategies. More description of the cost outputs are given below.

1. Estimate of total cost needed to apply selected combination of life extension strategies with a breakdown of costs per activity. These outputs will be available in both numerical and graphical format so that they facilitate cost comparisons between different strategies combinations and give the users insights into the cost contributions for each combination of strategies.
2. The net costs of applying single strategy within the combination of strategies, the gross duration of applying single strategy, the one-off cost corresponding to the combination of strategies selected and the penalty costs corresponding to every failed component.

Cost model architecture

The cost model collects data such as machine/component to estimate cost for, strategy to estimate cost for, etc., as inputs, and return the cost estimate of applying the strategy and its cost breakdown as outputs. The cost output is calculated based on data and knowledge stored in the cost model (Fig. 2).

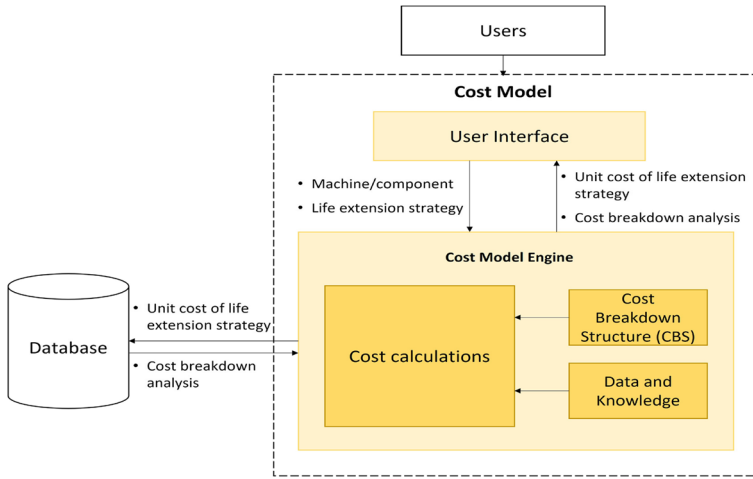


Fig. 2 Cost model architecture

Cost breakdown structure

The cost of life extension process has been generally classified into Disassembly Cost, Cleaning Cost, Inspection Cost, Replacement Cost and Assembly Cost. Each of these activities cost is composed of Labour Cost, Machine Cost and Consumables Cost, as shown in Fig. 3, the cost breakdown structure (CBS). Description of these cost elements are as below:

- *Labour Cost* ⇒ This cost is based on the time spent by the labour to perform the activity of life extension.
- *Machine Cost* ⇒ This is the cost of utilizing a machine to perform the activity of life extension.
- *Consumables Cost* ⇒ This includes the cost of any other resources that are used to perform the activity of life extension strategy (e.g., cost of any materials used in the activity process such as materials used in the Cleaning activity).

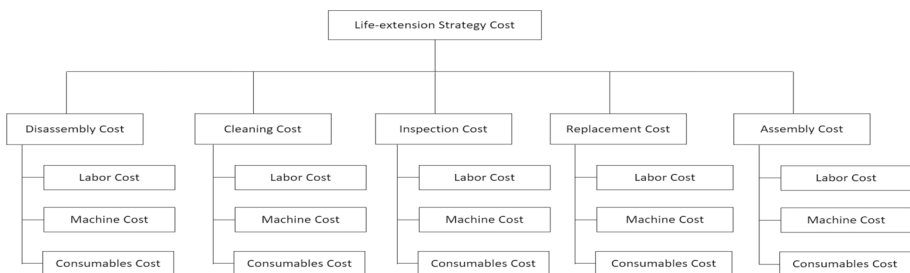


Fig. 3 Cost breakdown structure for life extension strategy

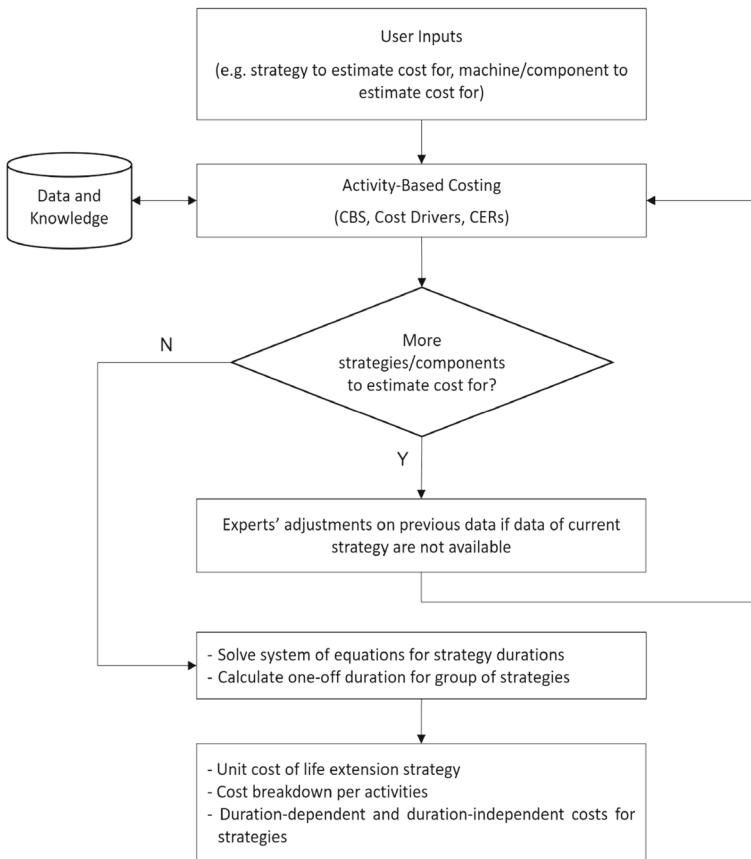


Fig. 4 Life extension cost estimation process

Life extension cost estimation

The framework of cost estimation presented in this paper adopts a combination of ABC method, parametric costing method and expert knowledge, as shown in Fig. 4. This includes using the ABC method to calculate cost of life extension strategy that has available data. Then, data used in calculating life extension strategy cost are adjusted by expert to estimate cost of other life extension strategies identified by users if data of that strategy was not available. Such approach of cost estimation is somewhat easy and fast to implement because if data of most strategies are not available, the set of data collected for one life extension strategy can be modified by expert to estimate cost of other life extension strategies. Then, a system of equations for combinations of strategies durations is developed and solved to calculate the one-off (common activities) duration for a group of strategies that need to be applied simultaneously in order to calculate the net duration-dependent cost of applying life extension strategy. The cost modelling outcomes will also allow for detailed analysis into estimated total cost to understand the cost difference between different life extension strategies for industrial equipment, which will help identify cost savings on long-term.

Unit cost and cost breakdown of life extension

This step explains how to calculate the total cost of applying life extension strategy and breakdown costs of activities, in order to allow the end-user to get insights into the life extension strategy costs and compare between different scenarios of life extension strategy application. Having defined the CBS, the next step is to generate mathematical equations for each cost element based on cost drivers. Cost drivers are those factors of life extension strategy process that directly explain the cost incurred by the activities in the process. An example of the main cost drivers for each activity of the proposed life extension strategy process include machine time and labour time.

The cost drivers rate and quantity consumed by each activity are determined (e.g. R is either the labour rate or machine rate (€/hour) and T is either the machine time or labour time (hour)). Then, the cost of each activity is computed based on cost drivers rate and quantity as shown in Eq. 1.

$$C_j = \left(\sum_{i=1}^k R_i \times T_i \right) + O_j \quad (1)$$

where C_j is the cost of j^{th} activity, k is the number of cost elements in activity j and O_j is the consumables cost during activity j .

The cost estimate process is continued in the same way for all activities, and the total cost of life extension strategy is then calculated by aggregating all costs of activities as per Eq. 2.

$$C_{total} = \sum_{j=1}^n C_j + F \quad (2)$$

where C_{total} is the total cost of applying life extension strategy and n is the number of activities. F is the penalty cost due to failure. This type of cost is estimated by the manufacturer/end-user and has been added to the model to distinguish between Corrective Maintenance, which usually happens to restore failed components, and Preventive Maintenance, which usually happens based on time schedule of condition prediction. The penalty cost, F , may of:

- *Urgency Cost* \Rightarrow Includes costs incurred due to urgency of applying the strategy, buying components, getting repair staff ready, detecting and diagnosing failure, etc.
- *Stoppage Cost* \Rightarrow Includes costs incurred due to stoppage of the production line.
- *Additional Cost* \Rightarrow Includes any additional costs incurred during repair works.

When data are not available, the cost of other life extension strategies can be estimated based on adjusting cost drivers' quantities in respect to existing life extension strategy data. For example, values of machine time, labour time and consumables cost for certain life extension strategy s are modified as percentages of the corresponding values of existing life extension strategy. Accordingly, we rewrite Eq. 1 to estimate cost of each activity of life extension strategy s as shown below (Eq. 3).

$$C_j^s = \left(\sum_{i=1}^k R_i \times (T_i \times \alpha_s) \right) + (O_j \times \alpha_s) \quad (3)$$

where α_s is the adjustment factor for life extension strategy s , which is for simplicity independent of activities j .

Cost of common activities for group of life extension strategies

This step explains the calculation of common activities cost (called “one-off cost” or “single time cost”) when applying a group of life extension strategies (i.e., two or more strategies) simultaneously, as well as the net duration cost of life extension strategy. The benefit of calculating the one-off cost is that it will be used to help identifying the long-term potential savings when applying a group of strategies simultaneously instead of single application of strategies over different times. Once the one-off cost has been calculated, it is subtracted from the gross duration cost calculated in “Unit cost and cost breakdown of life extension” section to obtain the net duration cost of applying life extension strategy. Equation 4 below presents the mathematical formulation of the durations’ system of equations for groups of life extension strategies, which will be used to obtain the one-off time needed to calculate the corresponding one-off cost.

$$\begin{aligned}
 a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n &= b_1 \\
 a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n &= b_2 \\
 \dots & \\
 \dots & \\
 a_{n1}x_1 + a_{n2}x_2 + \dots + a_{nn}x_n &= b_n
 \end{aligned} \tag{4}$$

where x_1 represents the duration of common activities (i.e., time needed to perform the common activities when apply multiple strategies at a time), x_2, x_3, \dots, x_n represent the duration of performing the rest of activities for a certain strategy within the combination, b represents the gross duration of performing the activities of strategy combination, and a is a coefficient which takes a value of 1 if the strategy is present in the combination and 0 otherwise. Note that a always takes a value of 1 for common activity duration (x_1) as it presents in every strategy combination.

The system of equations shown in Eq. 4 has been formulated into matrix form (Eq. 5) in order to perform matrix calculation and obtain the duration of common activities, x_1 (also called the one-off duration).

$$\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & & & \\ \dots & & & \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \dots \\ b_n \end{bmatrix} \tag{5}$$

Now, we obtain the one-off cost by multiplying x_1 and the one-off cost rate (e.g. labor rate and machine rate). Then, the net duration cost is calculated by subtracting the one-off cost from the gross duration cost. We can also calculate the duration-dependent cost by multiplying the one-off cost and duration of strategy.

Cost model implementation

The cost model presented in this paper has been demonstrated on a case study built around a friction welding machine (as shown in Fig. 5) from RECLAIM (REmanufaCturing and refurbishment LArge Industrial equipMent) project that has been launched to help European industry to improve productivity and performance by finding solutions for extending lifetime

Fig. 5 Friction welding system [51]



of ageing machines [50]. An Excel[®] macro tool was developed to implement the cost model. Details of the case study application and results obtained are described next.

Case study description

The friction welding machine of the case study was manufactured by Harms&Wende (HWH), Germany. Such welding machines are used for joining of welded metal parts including a huge variety of materials like steel, aluminium, ceramics, brass, copper, etc. The friction welding machine consists of a variety of electrical (motor, converter, controller, etc.) and mechanical (welding head, spindle, gear, clamping unit, frame, etc.) components that are relevant to maintenance tasks.

In this case study, four components (motor, spindle, sample-holder and sample-detector) have been identified as core components because they are the most degradable components and prone to failure. The rest of components in the machine, which are less degradable, are considered as one component and indicated as “rest-of-components”. Figure 6 shows the schematic diagram of modelled components. And Table 2 presents the components and life extension strategy corresponding to each.

The cost model allows the user to specify which type of life extension strategy to be applied and calculate cost for. Table 3 presents example of the scenarios for both single and multiple application of life extension strategies. For example, scenarios 1,2 and 4 show multiple application of strategies, while scenario 3 shows single application of strategy to certain component. Each component can have single or multiple strategies applied to it. based on Table 2, it can be seen that only two components (Motor and Spindle) can have multiple strategies application. The possible scenarios of strategies can then be concluded accordingly. The four scenarios presented in Table 3 represent a sample from the whole set of possible scenarios and meant to explain how different inputs of strategies might be in the cost model.

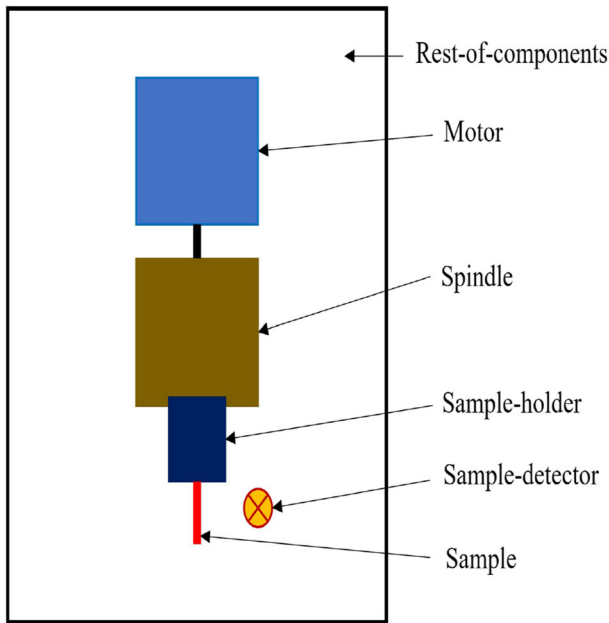


Fig. 6 Schematic diagram of modelled components [51]

Table 2 Components and corresponding life extension strategy

Component	Life extension strategy
Rest-of-components	Refurbishment
Motor	Replacement, Maintenance
Spindle	Replacement, Maintenance
Sample-holder	Replacement
Sample-detector	Replacement

Table 3 Scenarios of life extension experimented on cost model

Scenario	Components	Life extension strategy
1	Rest-of-components	Refurbishment
	Motor	Replacement
	Spindle	Replacement
	Sample-holder	Replacement
	Sample-detector	Replacement
2	Rest-of-components	Refurbishment
	Motor	Replacement
	Spindle	Maintenance
3	Motor	Maintenance
4	Sample-holder	Replacement
	Sample-detector	Replacement

Table 4 Normalised values of process-dependent data

Activity		Rest-of-components	Motor	Spindle	Sample-holder	Sample-detector
Disassembly	Time	0.45	0.45	0.45	0.45	0.45
	Consumables cost	0.20	0.20	0.20	0.20	0.20
Cleaning	Time	0.09	0.09	0.09	0.09	0.09
	Consumables cost	0.20	0.20	0.20	0.20	0.20
Inspection	Time	0.09	0.09	0.09	0.09	0.09
	Consumables cost	0.20	0.20	0.20	0.20	0.20
Replacement/ Maintenance	Time	0.10	0.10	0.10	0.10	0.10
	Consumables cost	0.20	0.20	0.20	0.20	0.20
Assembly	Time	0.27	0.27	0.27	0.27	0.27
	Consumables cost	0.20	0.20	0.20	0.20	0.20
Overall	Time	1.00	1.00	1.00	1.00	1.00
	Consumables cost	1.00	1.00	1.00	1.00	1.00

Case study application and results

The data and knowledge required for cost modelling have been collected, and then normalised for better analysis and cost comparisons of different life extension strategies. As example of such data, Table 4 shows the process-dependent data for life extension strategy application. This includes time and consumables costs needed to perform each activity normalised in respect to the overall activities. It is worth mentioning that time and consumables costs needed for conducting either replacement or maintenance strategy for “Motor” component are considered equal. Table 5 shows the process-independent data that includes the price of buying new component, refurbishment or maintenance independent of process time. The data value shown in Table 5 were normalised in respect to the highest price, which is the price of new spindle in this case.

As explained earlier, the users can conduct cost estimation either when single life extension strategy is applied or multiple life extension strategies are applied simultaneously.

Table 5 Normalised values of process-independent data

Parameter	Normalised Value
Price of New Motor - Type A	0.44
Price of New Motor - Type B	0.67
Price of New Motor - Type C	0.48
Price of New Spindle	1.00
Price of New Sample-holder	0.01
Price of New Sample-detector	0.01
Refurbishment Price of Rest-of-components	0.50
Maintenance Price of Motor (all types)	0.01
Maintenance Price of Spindle	0.01

User Inputs			Components Information						Penalty Cost due to Failure (€)
Pilots	Machines	Design Alternative	Name	Selected?	#	Failed?	Failure Type	Strategy Applied	
HWH	Friction Welding Machine	1	Rest-of-components (RoC)	Yes	1	Yes	Failure	Refurbishment	0
			Motor (M)	No	1	Yes	Mechanical	Replacement	
			Spindle (S)	Yes	1	Yes	Mechanical	Replacement	
			Sample-holder (SH)	Yes	1	Yes	Failure	Replacement	
			Sample-detector (SD)	Yes	1	Yes	Failure	Replacement	

Fig. 7 Cost model user inputs for scenario 1

Equations 1 through 3 are used to calculate cost of single life extension strategy based on activities performed, while Eqs. 4 and 5 are used when more than one strategy are applied at a time in order to identify the one-off cost (i.e., cost of common activities). This cost represents the extra cost to be incurred if each of the multiple strategies was applied separately and at different times. This system of equations approach allows to estimate the costs of any combination (scenario) of components/strategies so that less amount of data needs to be collected.

Having implementing life extension cost estimation process explained in “Life extension cost estimation” section, all scenarios listed in Table 3 have been experimented. As a first step, the user needs to enter the input values related to the particular life extension scenario, as seen in Fig. 7. The cells highlighted in yellow need to be defined by the user. These include which set of design alternative to be applied, the components need to be analysed within the scenario (this can be single component or group of components), the reason for applying life extension whether due to failure or as a predictive maintenance, type of failure (if applicable), life extension strategy to be applied to the component(s), and the penalty cost due to failure (if applicable). Then, the cost model is able to provide the cost analysis of the life extension scenarios.

Figure 8 shows the normalised cost comparison of scenarios made in respect to the cost of scenario 1 where all machine components either refurbished or replaced. Users can have an overview of the cost differences among input scenarios.

Figure 9 shows example of detailed cost output. The pie charts show the cost breakdown as percentages for the different life extension scenarios obtained from the cost model. These

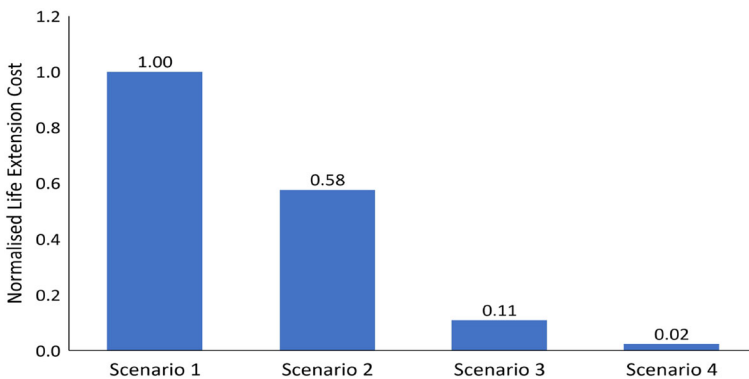


Fig. 8 Cost comparison of different life extension scenarios



Fig. 9 Activity cost distribution for experimented scenarios 1-4

cost results allow the users to get insights into the total cost and identify the main cost contributors to the life extension cost and compare the scenarios.

Figure 10 shows example of the total cost needed to apply life extension scenario, the net costs of applying single strategy within the scenario, the gross duration of applying single strategy, the one-off cost corresponding to the combination of strategies selected (scenario) and the penalty costs due to failure of the component(s).

Conclusion

The cost model introduced in this paper enables industrial manufacturers to economically investigate different scenarios of life extension strategies (e.g., remanufacturing, refurbishment, repair), understand the costs to be incurred when applying life extension strategy to their equipment and support determining the most cost-effective way forward. In this context, the cost model is composed of:

- *Cost Estimation Engine* ⇒ in which the cost of life extension strategy depends on multiple factors embedded within the cost model with other data and knowledge to allow users to estimate the cost of life extension strategy quickly. It integrates a combination of parametric costing and activity-based costing methods, takes into account several types of life extension strategies, the activities and resources needed for each activity.

Pilots	Machines	Design Alternative	Components Information						Cost/Duration of Strategy Application				Penalty Cost due to Failure
			Name	Selected?	#	Failed?	Failure Type	Strategy Applied	Gross Duration	Net Cost	Single Time Cost	Overall Cost	
HWH	Friction Welding Machine	1	Rest-of-components (RoC)	Yes	1	Yes	Failure	Refurbishment	1.0	0.24	0.02	1.0	0
			Motor (M)	Yes	1	Yes	Mechanical	Replacement	0.5	0.11			
			Spindle (S)	Yes	1	Yes	Mechanical	Replacement	0.5	0.60			
			Sample-holder (SH)	Yes	1	Yes	Failure	Replacement	0.06	0.01			
			Sample-detector (SD)	Yes	1	Yes	Failure	Replacement	0.06	0.02			

Fig. 10 Cost output for scenario 1

- *Cost Model Inputs* \Rightarrow includes input data from the users in order to perform calculations based on data and knowledge stored in the cost model.
- *Cost Model Outputs* \Rightarrow in which cost estimation results are available in both numeric and graphical format for better analysis and comparisons of different life extension alternatives to support optimal selection.

The data and knowledge used in developing and implementing the cost model have been confirmed by experts from RECLAIM project as being within the reasonable ranges. This was also the case for cost model outputs obtained from experimented case study.

The developed cost model provides users with cost index that helps evaluating the costs of applying life extension strategy (either single or multiple strategies) during machine downtime, so that they are able to evaluate economic benefit of strategy application to their machines at the current downtime and supporting decision making. This in turn will have an impact on the overall manufacturing system in terms of improving its durability, flexibility and sustainability. However, the developed cost model can also be integrated within a decision support framework to provide a long-term optimised decision on life extension strategy selection (i.e., which life extension strategy to be applied to the machine components and optimal time for intervention).

The developed cost model is suitable for any industrial manufacturer with large equipment to provide cost analysis and estimation and assist managers to decide among different alternatives of life extension strategies of their machines.

Acknowledgements The authors acknowledge all RECLAIM project partners for their support of the work.

Author Contributions Nasser Amaitik: writing-original draft, methodology, conceptualization; Ming Zhang: writing, methodology, conceptualization; Yuchun Xu: methodology, conceptualization, review and editing, supervision; Gareth Thomson: review and editing; Nikolaos Kolokas: review and editing, conceptualisation, resources; Alexander Maisuradze: review and editing, methodology, resources; Michael Peschl: review; Dimitrios Tzovaras: review.

Funding The work described in this paper is part of the RECLAIM project “REmanufaCturing and Refurbishment LArge Industrial equipMent” and received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 869884.

Availability of Data and Materials Not applicable.

Declarations

Ethical Approval Not applicable.

Consent to Participate The authors declare their consent to participate in this article and correctness of authors group, corresponding author, and the order of authors.

Consent to Publish The authors declare their consent to publish this article in “Journal of Remanufacturing”.

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Bakker CA, Mugge R, Boks C, Oguchi M (2021) Understanding and managing product lifetimes in support of a circular economy. *J Clean Prod* 279:123764. <https://doi.org/10.1016/j.jclepro.2020.123764>
- Patwa N, Sivarajah U, Seetharaman A, Sarkar S, Maiti K, Hingorani K (2021) Towards a circular economy: An emerging economics context. *J Bus Res* 122:725–735. <https://doi.org/10.1016/j.jbusres.2020.05.015>
- Nikolaou IE, Jones N, Stefanakis A (2021) Circular economy and sustainability: the past, the present and the future directions. *Circ Econ Sust* 1–20. <https://doi.org/10.1007/s43615-021-00030-3>
- Milius L (2018) Advancing to a circular economy: three essential ingredients for a comprehensive policy mix. *Sust Sci* 13(3):861–878. <https://doi.org/10.1007/s11625-017-0502-9>
- Wang Y, Zhu Q, Krikke H, Hazen B (2020) How product and process knowledge enable consumer switching to remanufactured laptop computers in circular economy. *Technol Forecast Soc Change* 161. <https://doi.org/10.1016/j.techfore.2020.120275>
- Yuan X, Liu M, Yuan Q, Fan X, Teng Y, Fu J, Ma Q, Wang Q, Zuo J (2020) Transitioning china to a circular economy through remanufacturing: A comprehensive review of the management institutions and policy system. *Resour Conserv Recycl* 161. <https://doi.org/10.1016/j.resconrec.2020.104920>
- Amaitik N, Zhang M, Wang Z, Xu Y, Thomson G, Xiao Y, Kolokas N, Maisuradze A, Garcia O, Peschl M, Tzovaras D (2022) Cost modelling to support optimum selection of life extension strategy for industrial equipment in smart manufacturing. *Circ Econ Sus*. <https://doi.org/10.1007/s43615-022-00154-0>
- Rajkumar G, Alagarsamy K (2013) A systematic review of cost estimation models. *J Glob Res Comput Sci* 4(5):33–36. www.jgrcs.info
- Hueber C, Horejsi K, Schledjewski R (2016) Review of cost estimation: methods and models for aerospace composite manufacturing. *Adv Manuf Polym Compos Sci* 2:1–13. <https://doi.org/10.1080/20550340.2016.1154642>
- NASA(2019)Nasa cost estimating handbook. Report, The National Aeronautics and Space Administration (NASA). <https://www.nasa.gov/content/cost-estimating-handbook>
- Masel DT, Judd RP(2007) Using bottoms-up cost estimating relationships in a parametric cost estimation system. In: 2007 ISPA-SCEA Annual Conference, p 1–9
- Ardiansyah R, Sutopo W, Nizam M (2013) A parametric cost estimation model to develop prototype of electric vehicle based on activity-based costing. In: 2013 IEEE International Conference on Industrial Engineering and Engineering Management. IEEE, p 385–389
- Curran R, Raghunathan S, Price M (2004) Review of aerospace engineering cost modelling: The genetic causal approach. *Prog Aerosp Sci* 40(8):487–534
- Niazi A, Dai JS, Balabani S, Seneviratne L (2006) Product cost estimation: Technique classification and methodology review. *J Manuf Sci Eng* 128:563–575
- Aamodt A, Plaza E (1994) Case-based reasoning: Foundational issues, methodological variations, and system approaches. *AI Commun* 7(1):39–59
- Watson I(1999) Case-based reasoning is a methodology not a technology. Springer, p 213–223
- Goodall P, Graham I, Harding J, Conway P, Schleyer S, West A (2015) Cost estimation for remanufacture with limited and uncertain information using case based reasoning. *J Remanufacturing* 5(1):1–10
- Ficko M, Drstvenšek I, Brezočnik M, Balič J, Vaupotic B (2005) Prediction of total manufacturing costs for stamping tool on the basis of cad-model of finished product. *J Mater Process Technol* 164–165:1327–1335. <https://doi.org/10.1016/j.jmatprotec.2005.02.013>
- Qin PP, Liu CJ, Shu JW, Yan LY (2016) A case-based reasoning cost estimating model of hydraulic cylinder remanufacturing. *World Scientific* p 232–238. https://doi.org/10.1142/9789813208322_0027
- Ghazalli Z, Murata A (2011) Development of an ahp-cbr evaluation system for remanufacturing: end-of-life selection strategy. *Int J Sust Eng* 4(1):2–15. <https://doi.org/10.1080/19397038.2010.528848>
- Bouaziz Z, Ben Younes J, Zghal A (2006) Cost estimation system of dies manufacturing based on the complex machining features. *Int J Adv Manuf Technol*. <https://doi.org/10.1007/s00170-004-2179-3>
- Qian L, Ben-Arieh D (2008) Parametric cost estimation based on activity-based costing: A case study for design and development of rotational parts. *Int J Prod Econ* 113(2):805–818. <https://doi.org/10.1016/j.ijpe.2007.08.010>
- Xu Y, Elgh F, Erkoyuncu JA, Bankole O, Goh Y, Cheung WM, Baguley P, Wang Q, Arundachawat P, Shehab E (2012) Cost engineering for manufacturing: Current and future research. *Int J Comput Integr Manuf* 25(4–5):300–314
- Langmaak S, Wiseall S, Bru C, Adkins R, Scanlan J, Söbester A (2013) An activity-based-parametric hybrid cost model to estimate the unit cost of a novel gas turbine component. *Int J Prod Econ* 142(1):74–88. <https://eprints.soton.ac.uk/193725/>
- Smith AE, Mason AK (1997) Cost estimation predictive modeling: Regression versus neural network. *Eng Econ* 42(2):137–161

26. Cavalieri S, Maccarrone P, Pinto R(2004) Parametric vs. neural network models for the estimation of production costs: A case study in the automotive industry. *Int J Prod Econ* 91(2),65–177
27. Camargo M, Rabenasolo B, Jolly-Desodt A, Castelain J (2003) Application of the parametric cost estimation in the textile supply chain. *J Text Appar Technol Manag* 3(1):1–12
28. Lawand L, Panarotto M, Andersson P, Isaksson O, Kokkolaras M (2020) Dynamic lifecycle cost modeling for adaptable design optimization of additively remanufactured aeroengine components. *Aerospace* 7(8)
29. Zhang X, Ao X, Jiang Z, Zhang H, Cai W (2019) A remanufacturing cost prediction model of used parts considering failure characteristics. *Robot Comput Integr Manuf* 59:291–296
30. Duverlie P, Castelain JM (1999) Cost estimation during design step: Parametric method versus case based reasoning method. *Int J Adv Manuf Technol* 15(12):895–906. <https://doi.org/10.1007/s001700050147>
31. Curran R, Kundu AK, Wright JM, Crosby S, Price M, Raghunathan S, Benard E (2006) Modelling of aircraft manufacturing cost at the concept stage. *Int J Adv Manuf Technol*. <https://doi.org/10.1007/s00170-005-0205-8>
32. Almeida A, Cunha J (2017) The implementation of an activity-based costing (abc) system in a manufacturing company. *Procedia Manuf* 13:932–939. <https://doi.org/10.1016/j.promfg.2017.09.162>
33. Susanti S, Yuniaristanto Y, Sutopo W, Astuti R(2020) Parametric Cost Estimation Model for Li-ion Battery Pack of E-motorcycle Conversion based on Activity Based Costing. <https://doi.org/10.20944/preprints202007.0684.v1>
34. Xu Y, Feng W (2014) Develop a cost model to evaluate the economic benefit of remanufacturing based on specific technique. *J Remanuf* 4(1):4. <https://doi.org/10.1186/2210-4690-4-4>
35. Xu Y, Fernandez Sanchez J, Njuguna J (2014) Cost modelling to support optimised selection of end-of-life options for automotive components. *Int J Adv Manuf Technol* 73(1):399–407. <https://doi.org/10.1007/s00170-014-5804-9>
36. Abbu SR, Gade BR, Windmark C (2022) Cost model for remanufacturing. *Adv Transdiscipl Eng* 267–278
37. Tan X, Xu Y, Early J, Wang J, Curran R, Raghunathan S(2007) A framework for systematically estimating life cycle cost for integrated wing. In: *The 7th AIAA Aviation Technology, Integration and Operations Conference (ATIO2007)*
38. Xu Y, Wang J, Tan X, Curran R, Raghunathan S, Doherty J, Gore D(2008) A generic life cycle cost modeling approach for aircraft system. Springer, p 251–258
39. Xu Y, Wang J, Tan X, Curran R, Raghunathan S, Doherty J, Gore D (2008) Manufacturing cost modeling for aircraft wing. *The 6th International Conference on Manufacturing Research (ICMR08)*. Brunel University, London, United Kingdom, pp 817–824
40. Xu Y, Wang J, Tan X, Early J, Curran R, Raghunathan S, Doherty J, Gore D (2008). *Life Cycle Cost Modeling for Aircraft Wing Using Object-Oriented Systems Engineering Approach*. <https://doi.org/10.2514/6.2008-1118>
41. Sabharwal S, Garg S (2013) Determining cost effectiveness index of remanufacturing: A graph theoretic approach. *Int J Prod Econ* 144(2):521–532
42. Zhou Z, Dai G, Wu Z(2014) Research of fuzzy cost model for selective disassembly planning. In: *3rd International Conference on Materials and Products Manufacturing Technology (ICMPMT)*
43. Qin P, Sun Y, Shu J, Yang C(2015) Estimation of the remanufacturing cost of engineering machinery hydraulic cylinder. In: *3rd International Conference on Advanced Information and Communication Technology for Education (ICAICTE)*
44. Ding Z, Jiang Z, Liu Y, Wang Y, Li C(2018) A big data based cost prediction method for remanufacturing end-of-life products. In: *51st CIRP Conference on Manufacturing Systems (CIRP CMS)*, vol. 7. p 21362–1367. <https://doi.org/10.1016/j.procir.2018.03.129>
45. Gavidel SZ, Rickli JL(2018) Remanufacturing cost analysis under uncertain core quality and return conditions: extreme and non-extreme scenarios. arxiv
46. Jiang Z, Ding Z, Liu Y, Wang Y, Hu X, Yang Y (2020) A data-driven based decomposition-integration method for remanufacturing cost prediction of end-of-life products. *Robot Comput Integr Manuf* 61
47. Rassõlkin A, Kallaste A, Orlova S, Gevorkov L, Vaimann T, Belahcen A (2018) Re-use and recycling of different electrical machines. *Latv J Phys Tech Sci* 55(4):13–23. <https://doi.org/10.2478/lpts-2018-0025>
48. Khalil J, Saad SM (2009) Gindy N An integrated cost optimisation maintenance model for industrial equipment. *J Qual Maint Eng* 15(1):106–118. <https://doi.org/10.1108/13552510910943912>
49. Bengtsson M, Kurdve M (2016) Machining equipment life cycle costing model with dynamic maintenance cost. *Procedia CIRP* 48:102–107. <https://doi.org/10.1016/j.procir.2016.03.110> . <https://www.sciencedirect.com/science/article/pii/S2212827116300804>. The 23rd CIRP Conference on Life Cycle Engineering
50. RECLAIM:(2021). <https://www.reclaim-project.eu/>
51. RECLAIM (2021) Reclaim: Pilot specification. Report

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Nasser Amaitik¹ · Ming Zhang¹ · Yuchun Xu¹ · Gareth Thomson¹ · Nikolaos Kolokas² · Alexander Maisuradze³ · Michael Peschl³ · Dimitrios Tzovaras²

Ming Zhang
m.zhang21@aston.ac.uk

Gareth Thomson
G.A.THOMSON@aston.ac.uk

Nikolaos Kolokas
nikolokas@iti.gr

Alexander Maisuradze
alexander.maisuradze@harms-wende.de

Michael Peschl
michael.peschl@harms-wende.de

Dimitrios Tzovaras
Dimitrios.Tzovaras@iti.gr

¹ Aston University, Aston Triangle, Birmingham B4 7ET, UK

² Centre for Research and Technology Hellas, Marousi, Greece

³ Harms & Wende GmbH & Co. KG, Hamburg, Germany