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Develop a cost model to evaluate the economic benefit of remanufacturing based on specific technique

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Abstract

Remanufacturing is a process of recovering used products to a like-new condition. It can potentially achieve considerable economic, environmental and social benefits in many applications. However, its economic benefit varies for different products and remanufacturing processes. This research aims to develop a framework and cost model to quantitatively evaluate the benefits of remanufacturing techniques to assist the decision making on end-of-life strategies. Additive manufacturing-based remanufacturing process has been modelled first, then cost breakdown structure for the process has been created, and the cost model has been developed. Validation of the cost model has been conducted based on expert judgement, and a case study has been carried out by using the developed cost model to compare the benefit of remanufacturing a specified component or making a new one.

Keywords: End of life; Remanufacturing; Product recovery; Cost estimation; Cost engineering; Economic benefit analysis

1 Introduction

Remanufacturing is a process of recovering the used products to a like-new condition [1]. It enables the customers to have products in lower cost and also enables the manufacturers to save raw materials and other production costs. Remanufacturing can potentially achieve considerable economic, environmental and social benefits.

In some high-tech industrial sectors, e.g. aerospace, remanufacturing is an appropriate strategy to be adopted because (1) high-value parts are well worth to keep if possible and still meet safety requirements; (2) Product Service System (PSS) business model is widely adopted by some manufacturers, such as the aero engine manufacturers Rolls-Royce Plc. and General Electric (GE), which makes remanufacturing possible because the used products are owned by the original manufacturers in the PSS model, and the logistic channel and customer relationships are relatively mature and (3) new techniques provide potential ways to remanufacture high-value parts.

Despite the potential benefits, remanufactured products still account a relatively small portion compared to new manufactured products in general. One of the reasons is the economic benefit of remanufacturing is not clear when considering variety of products to be remanufactured and variety of remanufacturing processes that can be used.

Some previous research have developed methods to assess remanufacturing and other end-of-life options in economic, environmental and social aspects. For example, the decision making approach has been used by a number of researchers. Dunmade introduced a sustainability-based approach for evaluating remanufacturing and other product recovery processes, which named 'product lifecycle extension techniques selection (PLETS)' model. This model designed by fuzzy logic and multi-attribute decision can score each product recovery process against the selected criteria [2]. Bufardi et al. proposed a multi-criteria decision aid (MCDA) approach to help manufacturers select suitable products for end-of-life alternatives (remanufacturing or other product recovery processes) [3]. Jun et al. developed a multi-objective algorithm to evaluate the end-of-life alternatives including remanufacturing [4]. Fernández et al. developed a fuzzy algorithm to select product recovery policies. In that algorithm, product characteristics such as product value, volume, useful life and customer characteristics (such as customer location) are considered as the variable factors [5]. Iakovou et al. designed the 'Multicriteria Matrix' methodology for decision making in end-of-life alternatives. Multi-criteria analysis was performed based on the residual value, environment impact, weight, quantity and ease of disassembly [6]. Ghazalli and Murata developed an analytical hierarchy process (AHP) with case-based reasoning (CBR) approach to support end-of-life strategy selection. The economic cost and environmental cost were selected as the evaluation criteria [7]. Jiang Z et al. [8] proposed a multi-criteria decision making (MCDM) model for selecting remanufacturing technology, the pair-wise comparison approach of the analytic hierarchy process (AHP) was employed for the remanufacturing technology portfolio selection.

Research has also been found particularly for assessing the economic benefit of remanufacturing and other end-of-life (EoL) options. Chen and Chang researched the economics of a closed-loop supply chain (CLSC) incorporating remanufacturing based on a newsvendor framework bearing case. The economic analysis was carried out at high level for the hybrid system (including both manufacturing and CLSC and remanufacturing) to support decision making at remanufacturing system level [9]. Sutherland et al. presented a cost model at system level, and the model is used to optimise the remanufacturing facility size. The model did not consider the variation of remanufacturing methods, it was not able to optimise the selection of EoL strategies [10]. Azadivar and Ordoobadi estimated the cost of remanufacturing at high level by taking into account the assembly cost, disassembly cost, inventory cost and disposal cost. The cost estimation was more focused on how to model the lot size of remanufacturing and build the impact of lot size in the cost estimation, and it did not consider the difference between different remanufacturing technologies and processes [11].

From the above-reviewed research, most of evaluation and cost estimation of remanufacturing and EoL options are conducted at high level (EoL strategy level); however, research on evaluating remanufacturing based on specific techniques and processes remains limited. This paper presents a study on how reliable cost estimation for remanufacturing can be realised by cost modelling at detailed techniques and process levels.

2 Remanufacturing process modelling

In this research, the investigated remanufacturing process is based on additive manufacturing technique, which delivers a wire to the working area and the wire is heated and melted and eventually deposited into the working area. This remanufacturing process consists of four phases, which are reverse engineering, data processing, depositing and grinding, as can be seen in Figure 1.

In Figure 1, the reverse engineering phase is to identify what areas/features to remanufacture. It consists of the following steps:

1) Returned products are measured by high-resolution digital cameras or any other contact or non-contact approach to build up the digital geometry of used part.
2) The digital geometry of the used part is compared with a reference model to identify the difference in geometry.

The data processing phase includes four activities: generating reconstruction specification, generating machining specification, generating tool path in the remanufacturing machine tool and simulating tool path. The reconstruction specification is transformed into machining specification, and then the tool path is generated. Simulation is conducted to pre-check the remanufacturing process at the beginning. The data processing step is normally carried out semi-automatically.

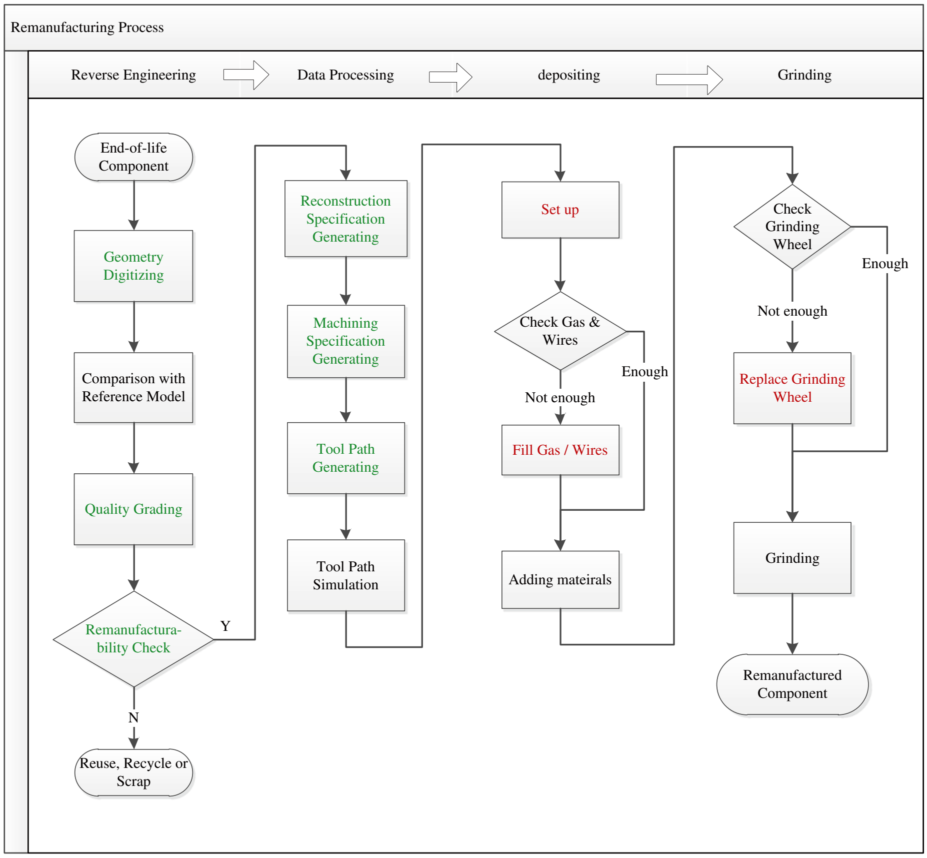


Figure 1 Additive manufacturing-based remanufacturing process model.

The machining process consists of two phases, which are depositing phase and grinding phase. The depositing phase includes setup, gas/wire check and adding materials; the grinding phase includes grinding wheel check and grinding process itself. Except the setup, other machining processes are operated automatically.

3 Cost model development

The cost model in this study was developed by following the cost estimation process suggested by the NASA Cost Estimating Handbook [12]. The key steps are explained in the following sections.

3.1 Cost estimation methodology selection

An appropriate cost estimating methodology needs to be selected first. The available cost estimating methodologies, such as parametric estimation [13-17], engineering build up estimation [18-22,16,23,17], analogy-based estimation and vendor quotes estimation [13,16], are compared in terms of required time, required resource, required data and scope of applications, as shown in Table 1. Letter H, M and L represent high, medium and low level for each term, respectively.

For the remanufacturing process based on additive manufacturing technique, there is no ready available history cost data about this process, so it is impossible to use parametric cost estimation method. Also, there is no similar valid remanufacturing cost estimation cases based on additive manufacturing technique, thus analogy-based estimation and vendor quotes estimation are not suitable in this study. Considering the data and resource available, engineering build-up cost estimation method has been selected for developing the cost estimation model in this study.

3.2 Cost breakdown structure development

The cost element associated with the remanufacturing process has been identified according to the process modelled. This identification process complies with the mutually exclusive and collectively exhaustive (MECE) principle, which means elements in the cost breakdown structure (CBS) should have ‘no overlaps’ and ‘no gaps’ [24]. The whole CBS is like a solid ‘pyramid’ without any omission and duplication.

According to this guideline below, the process is followed for CBS establishment. The first step is to define the first level of the CBS, this level covers all the major elements of the total remanufacturing cost, and also have no dependency between each other. After that, the lower levels of the CBS are developed based on the same principle until the level where cost value can be collected directly or calculated through the detailed remanufacturing process information. The CBS developed in this study is shown

Table 1 Features of cost estimating methodologies

	Time needed	Resource needed	Data needed	Scope of the method
Parametric estimation	M	M	M	M
Engineering build up estimation	H	H	H	H
Analogous estimation	L	M	H	L
Vendor quotes estimation	L	L	L	L

in Figure 2. As can been seen from it, the remanufacturing process includes three cost elements in the first level: pre-production cost, production cost and overhead cost.

1) Pre-production cost: Pre-production cost includes reverse engineering cost and data processing cost; both are labour-intensive costs and can be calculated by labour hourly rate and required working time.
2) Production cost: Production cost has been divided into three cost elements: setup cost, depositing cost and grinding cost. Setup cost is the labour cost of inputting the manufacturing specification, specifying the tool path and clamping the components onto the machine table. Depositing cost and grinding cost are machine-related costs, they can be divided into material cost, consumable cost (such as shielding gas cost, wheel replacement cost, cooling liquid cost, etc.),

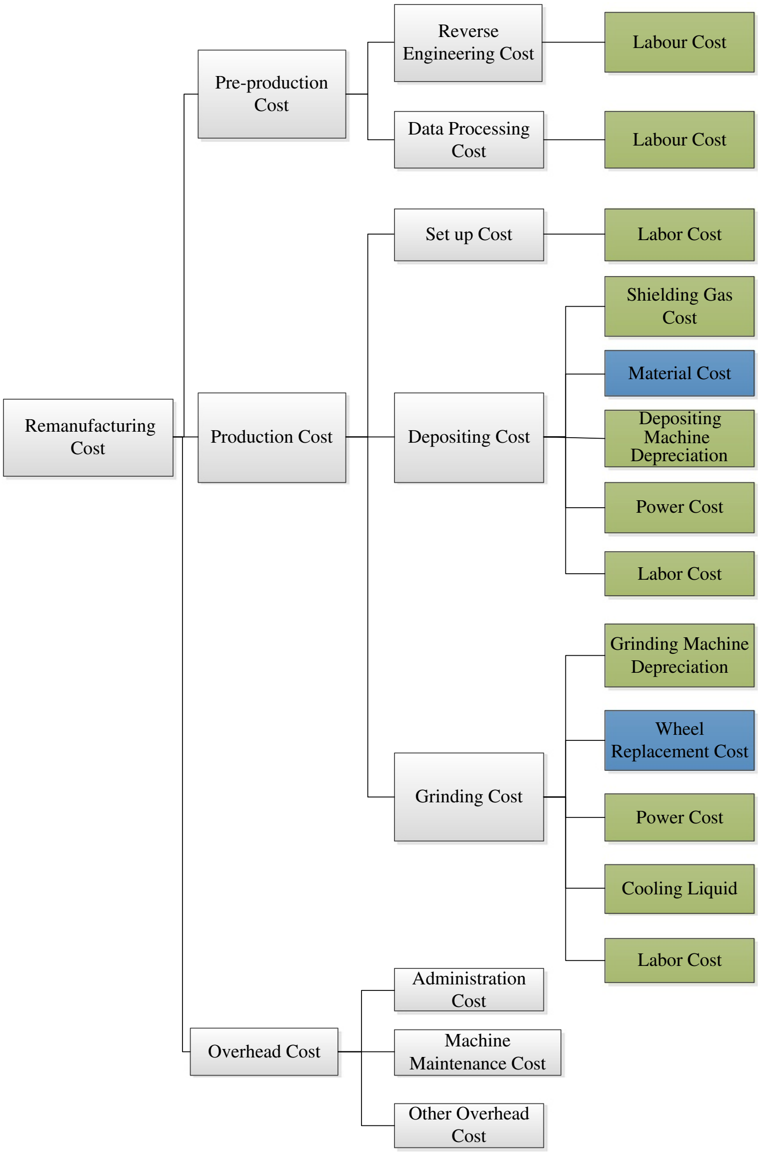


Figure 2 Cost breakdown structure for remanufacturing process.

machine depreciation cost, power cost and labour cost. Most of them (except material cost) are functions of operation time.

3) Overhead cost: The last cost element in the first level of the CBS is overhead cost. It includes administration cost, machine maintenance cost and other overhead cost, such as lighting, insurance cost, etc. As overhead cost is indirect cost, it varies by cases.

3.3 Cost driver identification

Cost drivers are those attributes of remanufacturing process that affect the cost of the different activities in remanufacturing process. The cost drivers have been mainly identified based on the information gathered from the author's knowledge, reviewed literature and interviewed field experts. The main cost drivers for each phase of remanufacturing process are listed in Table 2.

3.4 Cost estimation relationships development

Cost estimation relationships (CERs) need to be developed for each cost element in the CBS using the identified cost drivers. It means that each cost element is expressed as a function of the cost drivers. For example the labor cost of depositing and grinding process is calculated as below:

$$C_l = R_l \times \left(T_w + T_g\right) \tag{1}$$

where C_l is the labour cost (£), R_l is the labour hourly rate (£/h) and T_w and T_g are the times for depositing process and grinding process, respectively.

$$\mathrm{T}_w = \frac{T_d}{1 - i_w} = \frac{M_d}{D \times (1 - i_w)} \tag{2}$$

$$\mathrm{T}_g = \frac{T_{\mathrm{rm}}}{1 - i_g} = \frac{M_g}{R \times \left(1 - i_g\right)} \tag{3}$$

where T_d and T_{rm} are the deposition time in depositing process and material removal time in grinding process (h), i_w and i_g are the idle rate of depositing and grinding processes (%), D is the deposition rate of depositing machine (kg/h), R is the removal rate of grinding machine (kg/h).

In summary, the total cost of remanufacturing is calculated by aggregating all the cost elements:

$$C_{\mathrm{total}} = C_{\mathrm{pre}} + C_{\mathrm{set}} + C_w + C_s + C_g + C_d + C_l + C_p + C_o \tag{4}$$

where C_{total} is the total cost of remanufacturing, C_{pre} is the pre-production cost, C_{set} is the setup cost in the production stage, C_w, C_s and C_g are the cost of depositing material,

Table 2 Main cost drivers of remanufacturing process

Remanufacturing processes	Cost drivers
Reverse engineering	Complexity of the shape to remanufacture
Data processing	Complexity of the shape to remanufacture
Depositing	Volume of the part to remanufacture
	Complexity of the shape to remanufacture
Grinding	Volume of the part allowance to remove
	Complexity of the shape to remanufacture

shielding gas cost and grinding wheel consumption cost in the production stage, C_d, C_l, C_p and C_o are the machine depreciation cost, labour cost, power cost in the production stage and overhead cost, respectively.

3.5 Process parameters identification

The parameters of the remanufacturing process depend on the input parameters for remanufacturing and are determined by a knowledge base, which stores the relationship between these two sets of parameters. This knowledge base is designed previously based on the optimization results of experiments and the experts' experiences; this concept is shown in Figure 3.

The process parameters include deposition current and voltage, wire feed speed (WFS), travel speed (TS) and gas flow rate. Below is an example of knowledge-based rules used in Figure 3:

If material = aluminium (specification: 4,043 A),
and if geometry complexity = straight wall,
and if wall width = 5 mm,
then process current = 75 A, process voltage = 12.5 V, WFS = 4 m/min, TS = 0.4 m/min, gas flow rate = 16 L/min.

3.6 Cost model validation and implementation

The cost model has been validated conceptually on the cost estimation methodology, cost breakdown structure (CBS), cost estimating relationships (CERs) and cost estimation process by three experienced experts:

- Expert 1: A project manager of additive manufacturing project with more than three years of field experience has been used to validate the remanufacturing process model and process data.
- Expert 2: A cost engineering expert with over 10 years of experience in cost estimating has been used to validate the cost estimation methodology and the CBS.
- Expert 3: Another cost engineering expert with over 4 years of experience in cost estimating has been used to validate the cost estimation methodology.

In addition, the data collected in the cost estimation model also has been initially validated. The validation has confirmed that the data used in the cost model are within the

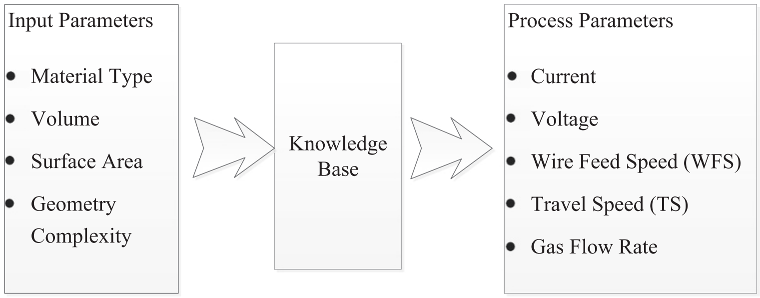


Figure 3 **Relationship between input parameters and process parameters.**

reasonable ranges; the cost model is developed logically and it is valid to meet the purpose of evaluating the economic benefit of remanufacturing based on specific techniques. The improvements made to the cost estimation model through the validation are as follows:

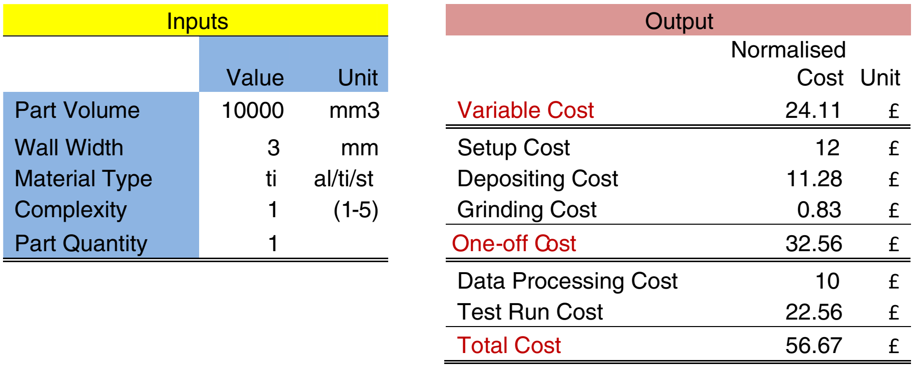
- In the remanufacturing process modelling, two scenarios of depositing equipment are considered in the depositing cost estimation. One is a robot arm assembled in a depositing machine, while the other one is a gantry combined with a depositing machine. Operators can choose a suitable setup for their needs in remanufacturing application.
- In the cost modelling, definition of an input parameter, geometry complexity, is revised for clarity so that the model users can input value correctly for their cases.

The cost model developed has been implemented in MS Excel® platform. Related depositing and grinding specifications are embedded into the spreadsheet. Figure 4 shows the model interface including input parameters and normalised outputs.

4 Case study

4.1 Remanufacturing of slat track

An end-of-life slat track has been selected to demonstrate the application of the developed cost model, i.e. to evaluate if this slat track is economically viable to remanufacture in comparison with making a new one. Slat track is a component linked to slats in aircraft wing, it conducts the motion trails of the slats. The slat track used in this study (as shown in Figure 5) is designed by Thomas Falvey in his MSc thesis at Cranfield



Inputs		
	Value	Unit
Part Volume	10000	mm3
Wall Width	3	mm
Material Type	ti	al/ti/st
Complexity	1	(1-5)
Part Quantity	1	

Output		
	Normalised Cost	Unit
Variable Cost	24.11	£
Setup Cost	12	£
Depositing Cost	11.28	£
Grinding Cost	0.83	£
One-off Cost	32.56	£
Data Processing Cost	10	£
Test Run Cost	22.56	£
Total Cost	56.67	£

Figure 4 Interface of MS Excel® based cost model.

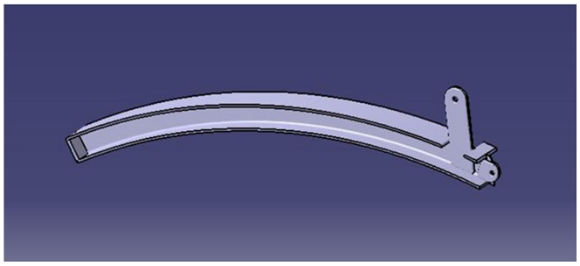


Figure 5 CAD model of the slat track.

Table 3 Geometry and material of the slat track

	Unit	Value
Volume	mm^3	1,013,700
Weight	kg	4.4887
Length (*Y*)	mm	910
Width (*X*)	mm	85
Height (*Z*)	mm	205

Material: Ti6Al4V.

University [25]. The related information about the slat track's geometry and material is shown in Table 3.

As part of the control mechanism, the slat track bears intensive cyclic stress, it tends to crack after a certain period in operation. In this study, an end-of-life slat track with damaged lugs is researched. The assumed geometry of the used slat track is shown in Figure 6. This slat track can be remanufactured by using additive manufacturing process to its original like-new shape shown in Figure 5.

The end-of-life slat track with damaged lugs has been analysed in reverse engineering stage. The reconstructed geometry is as shown in Figure 7. The reconstruction specification of the lug is shown in Table 4.

4.2 Cost distribution analysis

Cost distribution analysis is used to identify the main cost contributor, which accounts for the largest share of the total cost. A pie chart in Figure 8 shows the cost distribution in the remanufacturing process obtained from the developed cost model.

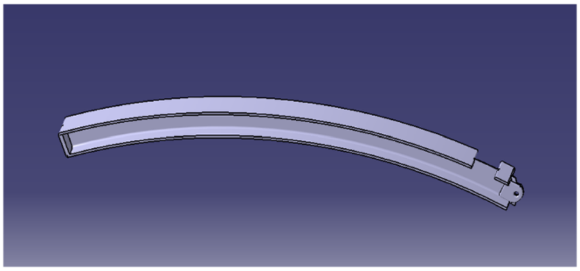


Figure 6 CAD model of the end-of-life slat track.

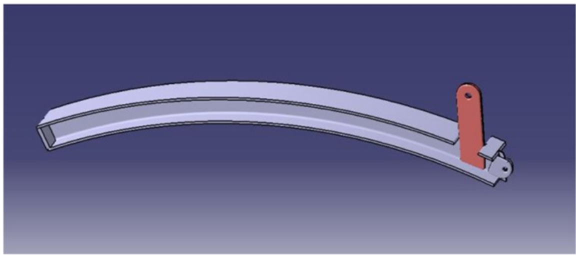


Figure 7 Reconstructed geometry of the end-of-life slat track.

Table 4 Reconstruction specification of the lug

	Unit	Value
Volume	mm^3	35,860
Weight	kg	0.3176
Length (*Y*)	mm	48
Width (*X*)	mm	7
Height (*Z*)	mm	178
Quantity		2

Material: Ti6Al4V.

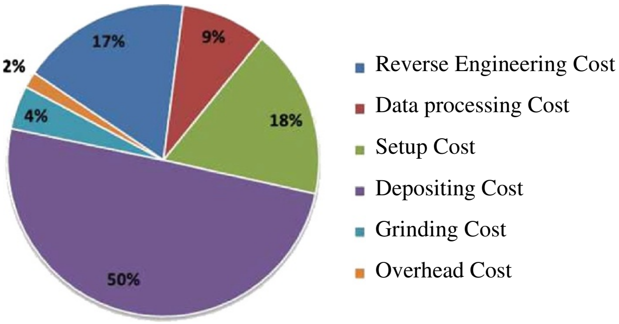


Figure 8 Cost distribution of the total remanufacturing cost.

The depositing cost has the largest share, which is about 50% of the total cost. The following big contributors are setup cost, reverse engineering cost and data processing cost, which are all pre-production activities. If these three cost elements are considered as an integrated one, the pre-production activities will account for around 44% of the total cost, which is the second biggest cost contributor. Because these activities are all manual or semi-automatic, the efficiency can be improved by using more experienced staff or by using more automatic process.

4.3 Comparison with traditional manufacturing

To assess the economic benefits of additive manufacturing-based remanufacturing option, the traditional production cost of the slat track is also calculated.

The raw material for manufacturing the slat track is a titanium block as shown in Figure 9. The traditional production process for this slat track is a combination of rough milling and finish milling, which has been modelled in Figure 10.

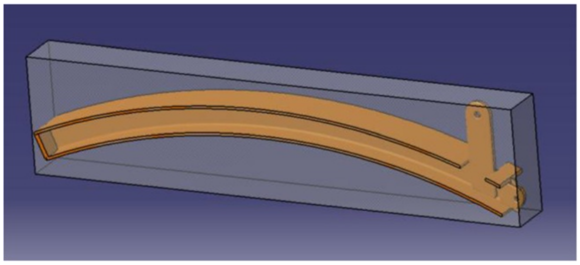


Figure 9 Raw material billet for manufacturing the slat track.

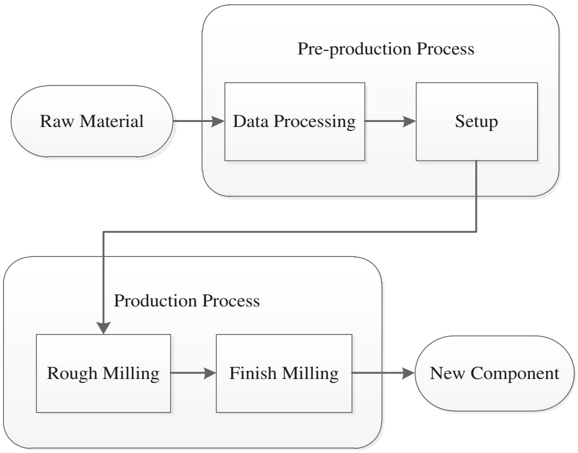


Figure 10 **Process model of traditional production of the slat track.**

For cost estimation of the new built slat track, SEER-MFG software has been used. The main input parameters used in this estimation are the same as used in the remanufacturing cost estimation in this study. The cost rates, like hourly labour rate and material unit cost are also the same as used in the remanufacturing cost estimation.

The result shows that by using additive manufacturing technique to remanufacture the selected slat track in this study, over 90% of the cost saving can be achieved in comparison with making a new slat track. This significant cost saving is achieved because of the raw material saving in remanufacturing, particularly in this case study the buy-to-fly ratio, reduces from 18 in making a new slat track to 1.12 in remanufacturing it.

5 Discussion and conclusion

In the analysis of economic benefit of remanufacturing as an EoL option, engineering build-up methodology for cost estimation can account for the details of specific remanufacturing techniques and processes. It was found that material type is a main cost driver in additive manufacturing-based remanufacturing process.

This cost model aims to evaluate the economic benefit of remanufacturing process based on specific techniques, so only the remanufacturing cost incurred in the remanufacturing premises is considered in this work. However for supporting decision making on end-of-life strategy (inc. remanufacturing) at high level, cost estimation of the whole remanufacturing system (including the cost of reverse logistics, inventory, etc.) need to be conducted.

Through this research, a cost estimation model based on engineering build-up methodology has been developed, the model has been initially validated by the experts and implemented in MS Excel® platform. The developed cost model has been used in a case study of remanufacturing a slat track in aircraft wing, and it is able to evaluate the economic benefit of remanufacturing process based on specific techniques. In this particular case study, the application of the developed cost model indicates that great cost saving can be made in remanufacturing the slat track than making a new slat track.

Authors' contributions
WF carried out literature review, developed the cost model and carried out case study. YX supervised the work and drafted the manuscript. All authors read and approved the final manuscript.

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