SPS2022
A.H.C. Ng et al. (Eds.)

doi:10.3233/ATDE220146

Cost Model for Remanufacturing

Spuran REDDY ABBU[a], Badri REDDY GADE[a] and Christina WINDMARK[a,1]
[a] *Division of Production and Materials Engineering, Lund University*

Abstract. Over the years, remanufacturing practices have grown in popularity in industrial areas. It is one of the most effective ways to keep products out of landfills by turning end-of-life items into usable products. However, the available literature on cost models is limited or specific to a product. A general cost model for remanufacturing is presented in this paper to understand the major costs involved in the process to aid decision-making. A model is developed based on activity-based costing and performance-based costing by considering both the activities that occur during the process and their performance. As a result of using the proposed model, it is easier to monitor the costs of each activity, changes in performance, and understand the resulting impact on the cost of finished products.

Keywords. Remanufacturing, Cost model, Decision making

1. Introduction

Our society needs to be more sustainable with less energy consumption and resource use. Reuse, remanufacture, and recycle are three ways to sustain a circular economy by prolonging the life of products. Reuse and remanufacture are the better alternatives to recycle in order to reduce waste and resources in the material loop. Remanufacturing is a process of restoring End of Life (EOL) products into a new product in a less cost and more efficient way [1]. As a result of remanufacturing practices, original equipment manufacturers (OEMs) are able to reduce operating costs, reduce lead times, and present a positive image to society as a whole [2]. Despite all these potential benefits the remanufacturing economic benefits are not completely clear when considering a variety of products and their processes that are used to remanufacture.

Over the years, many researchers have developed various methods to assess the product life extension through economic [3] [4] and environmental perspectives [5]. Generally, remanufacturing is a product-specific operation that differs from product to product and industry to industry. To make better decisions and to understand the economic parameters in a remanufacturing process, this paper aims to present a general cost model for remanufacturing. This model is intended to estimate the cost of remanufacturing activities and to assist in improving remanufacturing process.

The paper consists of a literature review on activities and operations involved in remanufacturing and current cost models for remanufacturing and manufacturing. The existing models are benchmarked to find gaps for improvements. Based on remanufacturing activities and the found gaps in existing models, a novel cost model is

---

[1] Corresponding author, Christina Windmark, Lund University Naturvetarvägen 18, 221 00 Lund, Sweden, E-mail: Christina.windmark@iprod.lth.se

presented and discussed. The model presented is based on a master thesis conducted in 2021 [6]. The parameters used in this paper can be found in section 2.

2. List of parameters

Parameter	Description	Parameter	Description
t_0	Cycle Time	K_M	Cost of a product brought from the customer.
t_p	Actual processing time	K_B	Total material cost for processing
T_{su}	Set up time	K_p	Total cost of coatings and paintings for processing a batch
T_{Plan}	Planned Production Time	K_{energy}	Yearly energy cost for equipment
q_P	Production Losses	$k_{paints/coating}$	Cost of Paints and surface coats per product
q_S	Downtime Losses	K_T	Total tool cost for processing a batch
q_Q	Quality Losses	k_{Tool}	Cost of tool per product/part
N_{in}	Number of parts/products entering a particular activity	$k_{storage}$	Storage cost per product
N_{out}	Output of a particular activity in terms of either parts or products.	K_{Area}	Yearly cost of area per square meter
N	Product's batch size	$K_{s.equip.}$	Annual cost of storage equipment used for storing a batch of size N.
N	Total number of batches handled in planned production time (T_{plan}).	Y	Total storage area in square meters used for storing a batch of size N
Z	Total number of various parts involved in a product	$k_{Material\ Hand}$	Cost of material handling per product
N_{OP}	Number of operators required	a_f	Annotation factor
N_{reman}	Number of remanufactured Parts	K_0	Basic investment
$N_{new/used}$	Number of new or Used parts	K_{MH}	Yearly maintenance cost
N_{ren}	Number of renovations	K_{fuel}	Cost of fuel for handling a product
N_P	Number of new/used products	A	The area tied to the material handling equipment
K_{CP}	Equipment hourly running time	K_A	Cost of additional process requirements for processing a batch
K_{CS}	Equipment hourly idle time	K_{APR}	Cost of additional process requirements per product
K_D	Operator cost per hour	$K_{New/used}$	Cost of new/used parts.
k_{old}	Avg. cost of old product	K_{IDC}	Additional hidden costs per product
$k_{add\ Mat}$	Cost of the virgin material added during part processing	$k_{Surface\ Treatment}$	Cost associated with whole surface treatment activity per product (includes k_{paint}, K_D, e.t.c.)

3. Methodology

In this study, a cost model for remanufacturing is developed based on the ABC model, which aligns a manufacture's resources and activities to its products or services in relation to its cost consumption. Unlike other costing methods (job costing method, direct costing, target costing), the ABC model identifies the cost associated with various activities involved in the process by identifying resources involved in each activity [4]. The major significance of this model is that it also incorporates indirect cost into the production activities. The ABC model provides the flexibility to divide the major operations into various activities and helps in understanding the cost associated with specific activity. This approach helps for developing a generalized model for various products which is quite important in remanufacturing. In the next step, cost drivers are selected for each type of cost, and the total cost is distributed between the products [7]. Along with this methodology, we have followed Ståhl's methodology where manufacturing literature is used to map important performance parameters also relevant for remanufacturing [8]. Ståhl's model has considered various performance parameters for estimating the cost of manufacturing a product which helps in combining economics with performance parameters in remanufacturing. In remanufacturing, it is important to balance both economic parameters and performance parameters. We have developed a cost model for remanufacturing, by adopting Stahl model in addition with ABC model. The methodology used in this study is to use academic literature to identify relevant activities in remanufacturing. In each activity resources and actions are mapped to be able to designate cost drivers and parameters. These cost drivers and parameters are combined in a model to capture the total cost of remanufacturing. which helps in both decision making and calculating accurate costs.

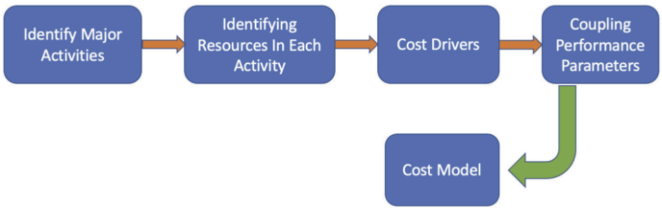

Figure 1. Basic schematic of remanufacturing cost model.

4. Literature review

4.1. The remanufacturing process

The remanufacturing process begins with the collection of EOL products that are functional and can be valuable for producing a new product with standard product quality [9]. Collecting the products is an important step in remanufacturing. Reimann et al. has demonstrated how to lower the cost of product recovery by leveraging closed loop chains between retailers and manufacturers [10]. A primary inspection is carried out to ensure the quality before recovering the product, which is commonly done at distributors or distributing centers [11]. If the products does not match the remanufacturing standards, it is further shipped to the recycling facility [12]. Inspection plays a vital role in remanufacturing. It's a time-consuming process where the products are assessed for remanufacturability. Errington and Childe argues that there are three stages of inspection, (i) core acceptance, (ii) part inspection (iii) final inspection [13]. First visual inspection is carried out on the cores to determines the economic feasibility of remanufacturing. Based on the complications the inspection time will vary from product to product. Part inspection is carried out on the dissembled part to evaluate the quality and eliminate the parts that are not recoverable. Reprocessing is performed on the parts with smaller defects like cracks, wear, and corrosion. The final inspection is similar to the traditional manufacturing process to ensure the functionality of the product [14]. In some cases, inspection is streamlined to use sensors and other technologies [15]. This multi-inspection ensures the quality of the product and gains the customer's trust for the remanufactured product [16].

Disassembly is a process of complete dismantling of cores. It is important to dismantle the core without damaging the parts. Disassembly is a manual process with equipment support. Due to the complex product design, the time taken for disassembly results in high operating costs [17]. Complex products come with a variety of challenges and the time it takes to dismantle them depends on the complexity [18]. All the functional dissembled parts go through a cleaning process like spar technique or water cleaning rest goes for disposal unit [19].

Reprocessing involves replacing non-functional components with brand new ones and repairing parts with minor defects [20]. Any minor defects that are noticed in the inspection can be eradicated through machining operations in this process [21]. The parts are transferred to the assembly lines. Similar to manufacturing, assembly involves the use of various tools and semi-automation to assemble the parts into final products [19].

4.2. Various cost models and their cost consideration

In remanufacturing various cost models have been developed for various purposes, most of the models are specific to a product or a process. Xu and Feng have developed a model focusing on additive manufacturing [19]. They have classified remanufacturing cost into 3 stages: (i) pre-production (ii) production (iii) overhead cost. The authors have illustrated how the cost drivers influence the cost of the remanufacturing. They have considered various additional processing costs involved in the process and this model mainly focuses on the material processing stage. Krill & Hurston model consists various economic and performance parameters in estimating the remanufacturing cost [22]. Their model confirms the need for primary inspection before remanufacturing process begins, to get precise results. Their study also illustrates the major activities and costs involved in each stage mentioned in 4.1, also argues that inspection cost is varied from product to product. Galbreth and Blackburn has developed a model to sort the cores/products for remanufacturing by setting maximum cut off-limits to purchase a product [23]. Jiang et al. has developed a model to assess the functional cost such as labor and machining costs [17]. Sutherland et al. has developed a model to examine the total annual expenditure of the facility [24]. They analyzed the impact of transportation cost and remanufacturing efficiency on the total cost. Hasanov and Jaber has developed a model with learning effects to improve the quality for recovered products and better utilization of inventory [25]. Schulz and Ferretti argue that product recovery is carried out in batches, in each recovery step some fixed costs have prevailed [26]. Azadivar and Ordoobadi model estimates the flow of products and argues that reassembly cost is high due to the smaller batch sizes [27]. Rohr et al. has developed a CAPEX model to assess the economics of EOL batteries. This model consists of various direct and indirect cost associated within the activities connected to remanufacturing where transportation is one of the main operations [28]. In table 1, the findings in literature related to cost parameters in remanufacturing operations are stated for better comparison and benchmark. In the table 1, it can be clearly seen that collection costs, core and material costs are the most used parameters when estimating remanufacturing costs, whereas the other parameters are more sporadic used depending on the application. The last two papers represent the parameters related to performance driven costs found in manufacturing cost literature [8, 31] showing the potential development of the model.

Table 1. Cost parameters found in remanufacturing and manufacturing literature. The columns in cursive text are related to manufacturing costs.

Parameter group	Parameters/Papers	[19]	[29]	[24]	[22]	[28]	[30]	[25]	[8]	[31]
Pre-production	Collection cost	x	x	x	x	x	x	x		
	Cleaning cost			x	x		x			
	Inspection cost			x	x		x			
	Disassembly cost				x					
Personnel	Salary costs	x			x	x			*x*	*x*
	Indirect labor					x	x		*x*	*x*
Material	Core cost	x	x	x	x	x		x		
	Material costs	x	x	x	x			x	*x*	*x*
	Replacement cost	x	x		x					
	Quality rate		x			x	x	x	*x*	*x*
Handling cost/transportation	Equipment costs	x		x		x				*x*
	Personnel costs	x				x				*x*
	Energy costs									*x*
	Time spent on order									*x*
	Building costs									*x*
	Transportation time			x		x				*x*
Storage costs	Utilization level									*x*
	Facility costs			x		x				*x*
	Personnel costs									
Equipment costs	Investment costs			x		x			*x*	
	Hourly equipment cost								*x*	*x*
	Renovation/maintenance costs	x				x			*x*	*x*
	Setup costs	x	x						*x*	*x*
	Cycle time		x	x				x	*x*	*x*
	Downtime								*x*	*x*
	Energy costs	x							*x*	*x*
	Utilization level								*x*	
	Idle time	x					x			
	Scrap rate					x				

A key factor that impacts the cost of remanufacturing is the time it takes to process a product or a part. Generally, in manufacturing operations the processing time depends on different performance parameters like downtimes, production rate losses, etc. The performance parameters described in [8] taken into consideration are the cycle time and the actual processing time. The cycle time is expressed as the sum of the actual value-adding time together with loading and unloading times of the equipment. It does not consider equipment losses whereas, actual processing time considers various losses like quality rejections (q_Q), downtime (q_s) and production rate losses (q_p) associated with processing equipment. The actual processing time is expressed according to equation 1 as the number of hours needed for processing a product or part [8].

$$t_p = \frac{t_0}{(1 - q_P)(1 - q_S)(1 - q_Q)} \quad (1)$$

The model is based on batch production where the setup time together with the total processing time represent the time to produce a batch (T_p) [8], according to equation 2.

$$T_p = T_{su} + x \cdot t_p \quad (2)$$

During the remanufacturing process, the batch size can vary for each activity and product. Along with the performance parameters mentioned in Ståhl et.al [8] also describing the equipment hourly cost ($K_{Equipment}$) and personnel hourly cost ($K_{Personnel}$) which have been modified to suit our model development as stated below.

5. Model Development

In general, the previous literature has divided the remanufacturing process into five major activities: inspection, disassembly, reprocessing, reassembly, and testing. In this paper the activities in a remanufacturing process are divided into three different stages: (1) Product inspection and disassembly, (2) Part processing and inspections, and (3) Product assembly, functional testing and surface treatment. The first and last stages are at product level whereas the second stage refers to each of the individual parts in the products. In the last step the scrapped parts are replaced with refurbished or brand-new parts to ensure the workability, quality and durability of the product.

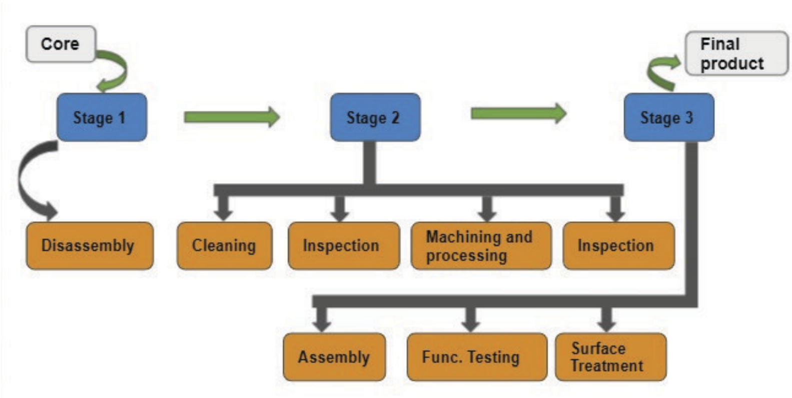

Figure 2. Classification of stages and activities in remanufacturing.

As described by Ståhl et al. [8] the cost of the processing equipment cost is calculated initially by knowing the equipment's hourly running (k_{CP}) and idle cost (k_{CS}). The hourly running/idle cost is multiplied with the time taken to process a batch (N_0) in an activity and then divided with the output of the activity [8] as shown in equation 3.

$$K_{Equipment} = \frac{k_{CP}}{N_{out}}\left(\frac{t_0 \cdot N_{in}}{(1-q_p)}\right) + \frac{k_{CS}}{N_{out}}\left(\frac{t_0 .\ N_{in}}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right) \quad (3)$$

Similarly, the personal cost is calculated as the equipment cost by considering the personal cost in hours and multiplied with the time taken to process a batch in an activity and then divided by the output of the activity according to equation 4.

$$K_{Personnel} = \frac{K_D \cdot N_{OP}}{N_{out}}\left(\frac{t_0 \cdot N_{in}}{(1-q_p)(1-q_s)} + T_{su}\right) \quad (4)$$

Along with equipment and personnel costs, we have a few other significant costs that must be considered in the presented model: cost for material, which consist of direct material consumables/additional material, and paint/surface treatment, tool costs, storage costs, material handling, and additional process requirements are included. The material cost ($K_{material}$) is associated with the used product (core) (k_{old}), the cost associated with added material in the machining activity (k_{addMat}), and the cost of paints and surface coats ($k_{Paints/Coats}$). The material of the core cost can be calculated according toto equation 5.

$$k_{old} = \frac{\sum_{i=1}^{N} K_M}{N_{in}} \quad (5)$$

Cost for material consumed in machining and material addition activity, according to equation 6.

$$k_{addMat}=\frac{K_B}{N_{out}} \quad (6)$$

In equation 7 the cost of paints and surface coats ($k_{paints/coats}$) per product can be seen.

$$k_{paints/coatings}=\frac{K_p}{N_{out}} \quad (7)$$

The cost associated with the tools used in machining activity for material removal purpose (k_{tool}) can be calculated as per equation 8.

$$k_{Tool}=\frac{K_T}{N_{out}} \quad (8)$$

It is important to keep in mind that storage costs ($k_{storage}$) can add significant costs to remanufacturing [31]. This cost can be considered as indirect cost since it does not add any value to the product. The storage cost associated with remanufactured products can be calculated according to equation 9, where inspiration is from [31].

$$k_{Storage}=\left(\left(\frac{Y\cdot K_{Area}+K_{s.equip.}}{\mathrm{N}\cdot\mathrm{n}}\right)\right) \quad (9)$$

Costs related to the transportation of parts and cores within the remanufacturing facility are known as material handling costs ($k_{material\ handling}$). The annual material handling costs will be based on the total number of products produced at the facility. The equation is based on the models presented in [8] and [31].

$$k_{Material\ Handling}=\frac{a_f\cdot K_0(1+K_0\cdot N_{ren})+K_{MH}+K_{Energy}+A\cdot K_{Area}+K_D\cdot N_{OP}\cdot T_{Plan}}{N\cdot n} \quad (10)$$

Additional process requirements cost (K_{APR}) consists of cost of various activities, and special requirements, such as cleaning agents in cleaning activities, welding gases for material addition activities are considered here. These activities include the costs associated with special requirements. Total APR costs are spread across the batch of products/parts produced in the activity, which serves as an indirect cost.

The total cost of remanufacturing can be calculated as mentioned in the methodology. The cost equation for every ingoing activity will be presented in the section 5.1 to 5.3.

5.1. Stage- 1 Product inspection and disassembly (K_1): $N_{in}=N_{out}=N$

The collected core will be brought from the warehouse to the disassembly station where the core is positioned in a fixed fixture by using power or semi-automated tools. The core will be dismantled and sent to the further processing as seen in **Figure 2**. The cost associated with the core will also be considered here since the value addition begins from this activity.

The major cost associated with this stage is the average cost of the core due to the varying cost of old products. The cost associated with fixtures and tools is considered as additional process requirements. Since remanufacturing is a labor-intensive process the cost of personal is considered. The cost for the disassembly activity can be calculated using equation 11.

$$K_{Disassembly} = K_{Old} + K_{Personnel} + K_{APR} \tag{11}$$

The total cost associated for stage 1 can be calculated by aggregating the activities considered in that stage, here only represented by disassembly as in equation 12.

$$K_1 = \frac{\sum_{i=1}^{N} K_M}{N} + \frac{K_D \cdot N_{OP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)\ (1-q_s)} + T_{su}\right) + \frac{K_A}{N} \tag{12}$$

5.2. Stage 2 Part processing and inspections (K_2): ($N_{in} = N_i$; $N_{Out} = N_{0i}$)

Stage 2 consists of various activities like cleaning, past inspection, machining and processing, and final inspection as you can see in the **Figure 2**. Once the core is dismantled, all the parts must be cleaned from contaminants like oils, grease, rust, and other foreign elements before going to part inspection. An appropriate cleaning method is chosen such as organic solvent cleaning technology, or electrolytic cleaning technology etc. Major resources in this activity are cleaning agents (APR), equipment, and personal. The cost for a part in cleaning ($K_{Cleaning}$) is calculated according to equations 13 and 14.

$$K_{Cleaning} = K_{Equipment} + K_{Personnel} + K_{APR} \tag{13}$$

$$\begin{aligned} K_{Cleaning} = &\left(\frac{K_{CP}}{N_i}\left(\frac{t_0 \cdot N_i}{(1-q_p)}\right) + \frac{K_{CS}}{N_i}\left(\frac{t_0 \cdot N_i}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) \\ &+ \left(\frac{K_D \cdot N_{OP}}{N_i}\left(\frac{t_0 \cdot N_i}{(1-q_p)(1-q_s)} + T_{su}\right)\right) + \frac{K_A}{N_i} \end{aligned} \tag{14}$$

The parts must be inspected for any damages, based on the complexity of the parts various methods are chosen. For example, inspection can be conducted manually or by using devices and sensors. The number of parts that meet the standards varies from batch to batch and core to core. The major resources here are personal and equipment used for part inspection and the cost can be calculated using equations 15 and 16.

$$K_{part\ inspection} = K_{Equipment} + K_{Personnel.} \tag{15}$$

$$\begin{aligned} K_{part\ inspection} = &\left(\frac{K_{CP}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)(1-q_Q)}\right) + \frac{K_{CS}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) \\ &+ \left(\frac{K_D \cdot N_{OP}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)(1-q_s)(1-q_Q)} + T_{su}\right)\right) \end{aligned} \tag{16}$$

After the part inspection the parts that have minor damages are machined, and new material is added to compensate for any losses from machining or other processes. The major resources in this activity are equipment's like CNC machines, new material is added for reprocessing the part, additional processes are required to make a proper value addition process and personal costs. The cost for machining and processing stage can be calculating by accumulating the activities considered in this process using equations 17 and 18.

$$K_{MM} = K_{add\ Mataterial} + K_{Tool} + K_{Equipment} + K_{Personnel} + K_{APR} \tag{17}$$

$$K_{MM} = \frac{K_B}{N_{0i}} + \frac{K_T}{N_{0i}} + \left(\frac{K_{CP}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p)}\right) + \frac{K_{CS}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p)(1-q_s)} + T_{su}\right)\right) + \frac{K_A}{N_{0i}} \tag{18}$$

The refurbished parts are inspected for dimensional accuracy and surface finish to ensure quality standards. If the parts fail to attain the desired quality, then they are sent back to Machining and material addition process. This can only be done limited times for economic reasons. For this activity the major resources are equipment used for testing and personal. The cost can be calculated according to equations 19 and 20.

$$K_{final\ inspection} = K_{Equipment} + K_{Personnel} \tag{19}$$

$$K_{final\ inspection} = \left(\frac{K_{CP}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p)}\right) + \frac{K_{CS}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p)\ (1-q_s)} + T_{su}\right)\right) \tag{20}$$

Therefore, the total cost of stage 2 can be calculated as described in equation 21.

$$\sum_{i=1}^{Z} K_2 = \sum_{i=1}^{Z} (N_{SP})(K_{Cleaning} + K_{part\ inspection}) + (N_{Reman})(K_{MM} + K_{final\ inspection}) + (N_{New/Used})(K_{New/used}) \tag{21}$$

All the activities in this stage are flexible and can be placed in any sequence. Based on the type of the product few activities can be avoided.

5.3. Stage-3 Product assembly, testing and surface treatment (K_3): $N_{in} = N_{out} = N$

Stage 3 consists of activities like assembly, functional testing, surface treatments as you can see from the **Figure 2**. The reassembly process is similar to the traditional assembly process where all the parts are assembled into a product. The cost for assembling a product ($K_{Assembly}$) can be calculated using equations 22 and 23.

$$K_{assembly} = K_{Personnel} + K_{APR} \tag{22}$$

$$K_{Assembly} = \frac{K_D.\ N_{OP}}{N}\left(\frac{t_0.\ N}{(1-q_p)\ (1-q_s)} + T_{su}\right) + \frac{K_A}{N} \tag{23}$$

The assembled products will undergo functional testing to ensure the products are suitable for real-world operations. The major resources here are equipment used for testing, other additional processes like fuel, and lubricating oils, and personal. The cost associated with functional testing ($K_{Func.Testing}$) of a product can be calculated using equations 24 and 25.

$$K_{Func.\ Testing} = K_{Equipment} + K_{Personnel} + K_{APR} \tag{24}$$

$$K_{Func.Testing} = \left(\frac{K_{CP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)}\right) + \frac{K_{CS}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)}\ \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)\,(1-q_s)} + T_{su}\right)\right) + \frac{K_A}{N} \tag{25}$$

The surface treatment is very flexible in terms of when it is performed in the stage. In this activity, the parts or the products are applied with surface coats and paints based on the requirement. It is also an optional process based on the product complexity. The major resources here are equipment for holding the part, personal cost, additional process The cost of a product surface treatment ($K_{surface\ treatment}$) cost can be calculated using the equations 26 and 27.

$$k_{surface\ treatment} = k_{paint/coating} + k_{Equipment} + k_{Personnel} + k_{APR} \tag{26}$$

$$k_{suraface\ treat} = \frac{K_p}{N} + \left(\frac{K_{CP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)}\right) + \frac{K_{CS}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)(1-q_s)} + T_{su}\right)\right) + \frac{K_A}{N} \tag{27}$$

Therefore, the total cost for processing a product in stage 3 can be calculated by using the equation 28.

$$K_3 = K_{Assembly} + K_{Func.\ Testing} + K_{surface\ treatment} \tag{28}$$

This is a breakdown of the various costs that are associated with major activities within the remanufacturing facility. Calculating material handling and storage costs for each activity makes the model complex, so we have taken the whole remanufacturing process of a specific product type into account. Along with all these costs there might be some hidden costs involved, like local storage equipment, etc. which are classified as additional costs ($K_{Additional}$).

$$K_{Additional} = \frac{\sum_{i=1}^{8} K_{IDC}}{N} \tag{29}$$

Summarizing all the above activities the total cost for remanufacturing ($K_{Remanufacturing}$) can be calculated according to equation 30.

$$K_{Remanufacturing} = K_1 + \sum^{z} K_2 + K_3 + K_{MH} + K_{Storage} + K_{Additional} \tag{30}$$

6. Discussions and conclusions

In many ways a remanufacturing process can be seen as an ordinary manufacturing process, with some characteristic differences related to batch sizes and product individual operations and treatments. However, the remanufacturing process is more labour intense process with multiple inspections involved to ensure the product quality and that the products meet the customer's expectations. Even though the remanufacturing products are the ones that have been manufactured, the purchase of the discarded products and cost of remanufacturing activities should not exceed the cost of new products. Therefore, it is important to monitor and improve remanufacturing operations, The model presented have the possibility to capture more different operations than many of the models captured in Table 1. The model presented in this paper is set out to capture the cost of whole remanufacturing process and identify the critical parameters in each stage of the process. The model aid in identifying and analysing various costs associated with in the entire process and provide better decision-making ability in remanufacturing practices. It provides a greater flexibility to adopt for various products. From the literature found on cost models for remanufacturing, the use of performance parameter such as downtime, setup time and speed rate losses are very marginal. Along with economical parameters this model also focuses on performances parameters to fill the gap from the existing literature. The major limitation of this model is it demands well-structured data for every input to give a precise cost. This model is best suitable for OEM's and large scale remanufactures. Future development is to test the model on a real case and to also include market demand factors. Another development would be to add profit margins for pricing of remanufactured products.

References

[1] M. Seitz, "A critical assessment of motives for product recovery: the case of engine remanufacturing.," *Journal of Cleaner Production,,* vol. 15, no. 11-12, pp. 147-1157, 2007.

[2] V. Guide Jr, "Production planning and control for remanufacturing: industry practice and research needs.," *Journal of operations Management,,* vol. 18, no. 4, pp. 467-483., 2000.

[3] R. Geyer, L. Van Wassenhove and A. Atasu, "The economics of remanufacturing under limited component durability and finite product life cycles.," *Management science,* vol. 53, no. 1, pp. 88-100, 2007.

[4] E. Sundin and B. Bras, "Making functional sales environmentally and economically beneficial through product remanufacturing," *Journal of cleaner production,* vol. 13, no. 9, pp. 913-925, 2005.

[5] M. Lindahl, E. Sundin and J. Östlin, " Environmental issues with the remanufacturing industry.," Proceedings of the 13th CIRP international conference on Life Cycle Engineering, Held at the Katholieke Universiteit Leuven, Belguim, Mai 31st-June 2nd, 2006.

[6] S. R. Abbu and B. R. Gade, "Development Of Optimized Cost Models for Recycling and Remanufacturing - A Step Towards Circular Economy," LUP Student Papers, Lund, 2021.

[7] R. Cooper and R. Kaplan, "Profit priorities from activity-based costing," *Harvard business review,* vol. 61, no. 3, pp. 130-135., 1991.

[8] J. Ståhl, C. Andersson and M. Jönsson, "A Basic Economic Model for Judging Production Development," in *Proceedings of the 1st International Swedish Production Symposium*, Gothenburg, 2007.

[9] E. Sundin and O. Dunbäck, "Reverse logistics challenges in remanufacturing of automotive mechatronic devices," *Journal of Remanufacturing,* vol. 3, no. 1, pp. 1-8, 2013.

[10] M. Reimann, Y. Xiong and Y. Zhou, "Managing a closed-loop supply chain with process innovation for remanufacturing.," *European Journal of Operational Research,* vol. 276, no. 2, pp. 510-518, 2019.

[11] Y. Awan and Q. Liu, "Network design for reverse logistics and remanufacturing under uncertainty.," in *IEEE 18th International Conference on Industrial Engineering and Engineering Management*, 2011.

[12] A. Alshamsi and A. Diabat, "A reverse logistics network design.," *Journal of Manufacturing Systems,,* vol. 37, pp. 589-598, 2015.

[13] M. Errington and S. Childe, "A business process model of inspection in remanufacturing.," *journal of Remanufacturing,,* vol. 3, no. 1, pp. 1-22, 2013.

[14] P. Lundmark, E. Sundin and M. Björkman, "Industrial challenges within the remanufacturing system," in *3rd Swedish Production Symposium* , Göteborg, 2009.

[15] J. Guide and L. Van Wassenhove, "the reverse supply chain," *Harvard business review,* vol. 80, no. 2, pp. 25-26, 2002.

[16] A. Brent and R. Steinhilper, "Opportunities for remanufactured electronic products from developing countries: hypotheses to characterise the perspectives of a global remanufacturing industry," in *EEE.*, Africa, 2004.

[17] Z. Jiang, T. Zhou, H. Zhang, Y. Wang, H. Cao and G. Tian, "Reliability and cost optimization for remanufacturing process planning," *Journal of cleaner production,* vol. 135, pp. 1602-1610, 2016.

[18] P. Zwolinski and D. Brissaud, "Remanufacturing strategies to support product design and redesign," *Journal of Engineering Design,* vol. 19, no. 4, pp. 321-335, 2008.

[19] Y. Xu and W. Feng, "Develop a cost model to evaluate the economic benefit of remanufacturing based on specific technique.," *Journal of Remanufacturing,* vol. 4, no. 1, pp. 1-12, 2014.

[20] M. Andrew Munot, R. Ibrahim and E. Junaidi, "An overview of used-products remanufacturing," *Mechanical Engineering Research,* vol. 5, no. 1, p. 12, 2015.

[21] T. Chmielewski and D. Golański, "The role of welding in the remanufacturing process.," *Welding International,* vol. 29, no. 11, pp. 861-864., 2015.

[22] M. Krill and D. hurston, "Remanufacturing: Impacts of Sacrificial Cylinder Liners." ASME. J. Manuf. Sci. Eng. 127(3), pp. 687–697, 2005.

[23] M. Galbreth and J. Blackburn, "Optimal acquisition and sorting policies for remanufacturing," *Production and Operations Management384-392.,* vol. 15, no. 3, pp. 384-392, 2006.

[24] J. Sutherland, T. Jenkins and K. Haapala, "Development of a cost model and its application in determining optimal size of a diesel engine remanufacturing facility.," *CIRP annals,* vol. 59, no. 1, pp. 49-52, 2010.

[25] P. Hasanov, M. Jaber and S. Zolfaghari, "Production, remanufacturing and waste disposal models for the cases of pure and partial backordering," *Applied Mathematical Modelling,* vol. 36, no. 11, pp. 5249-5261, 2012.

[26] T. Schulz and I. Ferretti, "On the alignment of lot sizing decisions in a remanufacturing system in the presence of random yield," *Journal of Remanufacturing,* vol. 1, no. 1, pp. 1-11, 2011.

[27] Azadivar, Farhad, and Sharon Ordoobadi. "A simulation model to justify remanufacturing policies." In Proceedings of the 2010 Winter Simulation Conference, pp. 1592-1600. IEEE, 2010.

[28] S. W. S. Rohr, M. Baumann, S. Müller and M. Lienkamp, "A techno-economic analysis of end of life value chains for lithium-ion batteries from electric vehicles. Twelfth International Conference on Ecological Vehicles and Renew," 2017.

[29] I. Masudin, F. Jannah, D. Utama and D. Restuputri, "Capacitated remanufacturing inventory model considering backorder: A case study of indonesian reverse logistics.," *IEEE Access,* vol. 7, pp. 143046-143057, 2019.

[30] P. Qin, S. Yun and J. Shu, "Estimation of the remanufacturing cost of engineering machinery hydraulic cylinder.," in *3d International Conference on Advanced Information and Communication Technology for Education*, 2015.

[31] C. Windmark and C. Andersson, "Cost models of inbound logistics activities: supporting production system design.," *International Journal of Supply Chain and Operations Resilience,* vol. 1, no. 2, pp. 181-200, 2015.