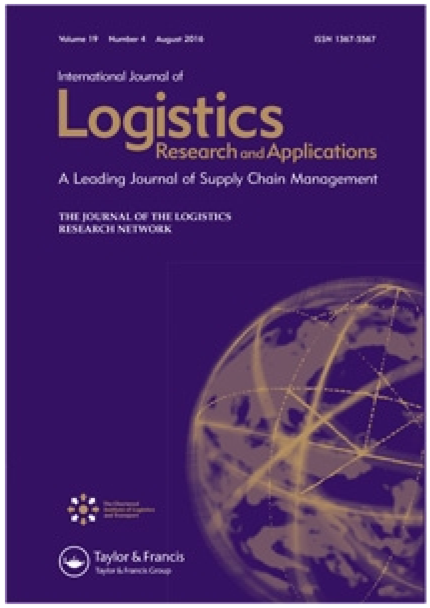
# Optimal number of remanufacturing in a circular economy platform

CESUR, E, CESUR, MR, KAYIKCI, Yasanur <http://orcid.org/0000-0003-2406-3164> and MANGLA, SK

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# Optimal Number of Remanufacturing in a Circular Economy Platform


## Abstract

In reducing waste and protecting natural resources benefits in a circular economy platform, performing remanufacturing tasks are complex, as it may be associated with costs such as investment, setup and disposal cost. Thus, many studies those aims to find the optimal number of remanufacturing has been investigated whether it is an infinite or a constant number of remanufacturing via trial-and-error method. During the investigation, the disposal rate is assumed as a fixed value for each unique case, which needs further focus. The current study aims to propose a novel decision model to figure out an optimal number of remanufacturing regarding to the various ratio of used units returned for recovery. The proposed model was extended in context of remanufacturing opportunities of PVC products. The obtained findings are useful for companies in managing remanufacturing processes by knowing optimal remanufacturing times, and results in enhanced economic-ecological-social gains in the circular economy.


**Keywords**: Circular Economy, Remanufacturing Rate, Optimal Remanufacturing Times, Sustainable Production, Green Supply Chain, PVC products

## 1. Introduction

Remanufacturing proves to be a significant process for sustainable production systems because of the benefits of reducing resource consumption (Lei et al., 2018), energy conservation (Zhu et al., 2019), carbon emission (Zhang et al., 2020) and production lead-time (Singhal et al., 2020). Remanufacturing requires the purchase of used products from the end user at the end of their current life cycle so that added value can be recovered and products can be returned to functional use again (Jayaraman et al., 2008). An effective management of this process can generate huge economic-ecological-social gains for manufacturing systems that cannot be ignored (Fleischmann et al., 1997). Therefore, the subject of remanufacturing is among a focal area of research for scholars all across the globe (Govindan et al., 2015).

In era of circular economy, the high-speed flow of products in the supply chain due to the increase in customer demand leads to over-utilization of natural resources (El Saadany and Jaber, 2010). Hence, industries have proposed some solutions for extracting maximise value from resources in use, which are mostly included in the field of supply chain and logistics management, not only to manage this improvement and to find the best possible cost reduction methods but also to collect used and returned items to recover or repair the used product (Madaan et al., 2012; Bhattacharjee and Cruz, 2015). As an open and digital marketplace, circular economy platform plays a prominent role to bring companies together and to support their collaborative activities through circularity (Schwanholz and Leipold, 2020) such as to use secondary raw materials of the material from one industry to another industry (Genovese et al., 2017; Kazancoglu et al., 2020). Adding to that, Teunter (2001) stated that remanufacturing has become more popular among practitioners due to strict environmental regulations and interest in environmentally friendly practices. The critical problem in recoverable manufacturing involving remanufacturing is an easy access to used products (Jayaraman et al., 2008), therefore, circular economy platform is required to meet right remanufacturing partners. There is a growing trend especially among large companies to include remanufacturing in their businesses for competitive gains. Furthermore, the remanufactured products or components can achieve even better performance and quality than a new one (Wang et al., 2020) as they save almost 50% of the energy, 33% of labour force and up to 80% raw materials compared with the newly manufactured products (Liu et al., 2019; Van Nguyen et al., 2020) and cost up usually 50%-70% less than the new one (Cao et al., 2020). For instance, in Germany, almost

10 % of automobile parts, like engines, starter engines, or alternators are remanufactured (Bras, 2007). Several car manufacturers, including BMW and Volkswagen offer remanufactured engines and other parts as fully-warrantied service parts (Flapper et al., 2006) and they aim to accelerate the upgrading of older cars and boost domestic demand (Li et al., 2019). In nutshell, companies benefit from both manufacturing and remanufacturing to make more profit.

From this point of view, the purpose of this research is to derive the optimal number of remanufacturing and to place the corresponding several remanufacture rates for circular economy platform in order to enhance green and sustainable supply chain management. This can prevent economically expired products, as those have reached the end-of-life for remanufacturing, from being put into production. In addition, the rate of waste or poor quality may cause an increasing cost in each remanufacturing process to which the material will be exposed (Zhang et al., 2020). Therefore, remanufacturing can be performed only for a finite number of times, because the product is no longer economically feasible or practical to remanufacture. Due to chemical properties of materials and the conditions of the production processes, materials may not be suitable to remanufacture after a certain number. At this point, manufacturing or remanufacturing trade-off must be taken into account in a remanufacturing model that aims to minimize total cost, otherwise it should be replaced with a newly manufactured product.

This research raises following research questions:

RQ1: How many times a product can be remanufactured optimally?

RQ2: Can the remanufacturing rate ($\beta$) be considered as a variable parameter expressed by a linear function?

RQ3: Which parameters are used to calculate the optimal number of remanufacturing, and further what are the effects of these parameters in determining optimal number of remanufacturing times?

In this study, we developed a decision model. Also, various scenarios in order to measure the effect of used parameters in the model are generated. Finally, the model is also illustrated with simulation experiments. Furthermore, the result of the simulation experiment is present to prove the applicability of the model. The central methodological contribution of this study highlights that a product can be remanufactured a finite number of times and find the optimal number of remanufacturing, secondly discovers optimal times considering the variability of remanufacturing rate in progress of time.

The remainder of this paper is organized as follows: Section 2 provides a literature review, which discusses the major research on remanufacturing models and highlights research gap. Section 3 gives problem definition and theoretical backgrounds and develops the proposed model for optimal number of remanufacturing. This is followed by Section 4, which describes a simulation experiment with scenarios to use in this study. Then Section 5 discusses the results and give more managerial insights on the effects of different parameters on optimal remanufacturing times. The paper summarizes and concludes the entire work in Section 6.

## 2. Literature Review

Practicing a green and sustainable supply chain is an important step in improving the competitive image of the companies amidst global climate change pressures (Gandhi et al., 2016; Genovese et al., 2017). One of green and sustainable supply chain practices is closed-loop supply chain, which engages in practice of taking back products from customers and returning them to the original manufactures in exchange for value by reusing whole or part of the products (Zhen et al., 2019; Islam et al., 2020). There is a large volume of published studies describing the closed-loop supply chain management in the field of both business and science (Ilgin and Gupta, 2010; Govindan et al., 2015), where remanufacturing is a sustainable and profitable practice for product recovery and also still nascent area notably in the developing countries and even in some developed countries (Rathore et al., 2011; Abdulrahman et al., 2015). Remanufacturing recovers a product as a whole and brings it up to an “as-new” quality (Teunter, 2002). A lot of remanufacturing related research has developed models for a variety of performance analysis and remanufacturing decision problems (Ilgin and Gupta, 2012; Sitcharangsie et al., 2019; Assid et al., 2019). The first model with item returns was conducted by Schrady (1967), who developed an Economic Order Quantity (EOQ) model for stock management of the repairable items that determines the optimal quantity of units to be supplied and repaired. Nahmias and Rivera (1979) improved this model by placing a restriction on the number of repair or recycling times. Richter (1996b) carried out a number of investigations about EOQ repair and waste disposal model. In his next studies, he enhanced the EOQ model by adding various setup numbers (Richter, 1996a) as well as by analysing both pure and mixed strategies (Richter, 1997), the optimal number of remanufacturing based upon the different values of the return rate was determined. In this study, Richter (1997) offers two strategies for pure policy called bang-bang policy: it assumes either "dispose all policy", that means that there is no any product which can be remanufactured or "recover all policy", that means that all products will be remanufactured, in other words, there is no any waste disposal at the place. Teunter (2001) based his study upon (Schrady, 1967), however, their study handled the policy differently and defined two-unit lots, which are manufacturing lot and remanufacturing lot. Besides, their study evaluated disposal rate and differentiated the holding cost in terms of manufacturing case and remanufacturing case. Moreover, Dobos and Richter (2004) investigated on manufacturing/remanufacturing model not only taking account with a constant demanded product and given back product rate but also dealing with the linear total cost function. El Saadany and Jaber (2008) examined the optimal amount of production and product, which are recovered from the market by using EOQ model. This paper defines a cycle, which is composed of manufacturing and remanufacturing steps, and this cycle firstly starts with producing new units. Then, the collected products will be added on the finished products stock after remanufacturing. In later study of El Saadany and Jaber (2010), they claimed that the quality and price of products effects the quantity of returned products. Besides, they pointed out at the same time that the mixed strategy, that means the combination of both manufacturing and remanufacturing, is more efficient than pure (recover/dispose) strategy. Ilgin and Gupta (2010) analysed that remanufacturing involves the accurate estimation of product returns, production planning and scheduling, capacity planning, and inventory management. Further, El Saadany et al., (2013) put a new study forward which is about finding out the number of optimal manufacturing and remanufacturing times. This kind of problem has emerged because of the trade of two fundamental cost parameters: investment cost and remanufacturing cost. Meanwhile, the finite remanufacturing assumption causes a significant erroneous which increase depending on the number of returned items. Guo and Ya (2015) developed a hybrid model to analyse optimal strategies for manufacturing and remanufacturing, where the demand rate is constant and the remanufacturing cost, the returns rate and the buyback cost depends on the minimum quality level of recycled products. Bazan et al., (2015) studied the effect of factors such carbon emissions and energy effects on manufacturing-remanufacturing decision in a proposed model, then this model was improved with a two-level closed-loop supply chain by Bazan et al., (2017) considering energy factors used for manufacturing and remanufacturing as well as greenhouse gas emissions from manufacturing, remanufacturing and transportation activities. In conclusion, this model was improved by Hasanov et al., (2019) with four-level closed-loop supply chain with remanufacturing and they found out that savings can be more substantial, if such a tax and subsidies are accounted in the developed model, as the number of remanufacturing times increases. Farahani et al., (2019) developed an optimal disposition policy for remanufacturing systems with variable quality grades of product returns and a limited recoverable products inventory capacity. Liu et al., (2019) proposed optimal pricing and production strategies for new and remanufactured products under a non-renewing free replacement warranty. Lieckens et al., (2020) built a stochastic, profit-maximizing model to determine the optimal remanufacturing network design with an exchange option for fast- and slow-moving part types.

After reviewing the existing literature in the field of remanufacturing, the research gap shows that there is no research that conducted to propose a model to show how many times a product should be remanufactured. This model can help to meet the requirements of green and sustainable supply chain management as well as to find appropriate remanufacturing partners on the circular economy platform. In addition, the remanufacturing rate in the existing literature is taken as a fixed value rather than being variable.

## 3. The proposed model

In this section, the model for optimal number of remanufacturing is described in detail. Problem definition, theoretical background and model proposal are also given.

### *3.1. Problem Definition*

In the literature, most of the studies on the closed-loop supply chain acknowledge that a product could be remanufactured in an unlimited number of times. However, El Saadany et al., (2013) not only claimed that it does not reflect the truth but also, developed a model of unit, which shows that a product is able to be remanufactured in a certain number of times. Also, Teunter (2001) proposed a model with a certain lot size for remanufacturing with taking into account manufacturing and remanufacturing costs.

In our study, the proposed model is developed in a setting with limited remanufacturability based on the extension of El Saadany et al., (2013) and Teunter (2001)'s models in terms of three aspects:

1) The disposal rate is variable per unit time.

2) A product can be remanufactured with an optimal number of times. This can be calculated by using a mathematical formulation instead of a numerical analysis with trial-and-error method, which causes a huge computational workload. It is not possible to consider all alternative results during the numerical analysis, so the optimal solution may not be considered.

3) Fractional amount of items namely remanufacturing rate, which are recovered, could be defined with a linear function which is much suitable to model real life cases.

### *3.2. Theoretical background*

In order to explain the theoretical background of the study, two seminar works of El Saadany et al., (2013) and Teunter (2001) are considered as basis. The models offered by these two-seminar works are investigated comprehensively to put forward the contribution of this research.

#### *3.2.1. The model of El Saadany et al., (2013)*

The proposed model of El Saadany et al., (2013) covers the effects of a limited remanufacturability on the material flows in a production remanufacturing system. For this model, notations are listed in Table 1 as follows:

*Table 1 - Notation of El Saadany et al., (2013)'s model*

| *Symbol* | *Explanation* |
|---|---|
| $\beta$ | fractional amount of items, which are recovered $(0 < \beta < 1)$ |
| $\zeta$ | number of times an item can be remanufactured |
| $\beta_\zeta$ | fractional amount of items, which are recovered $\zeta$ times $(0 < \beta_\zeta < \beta)$ |
| $\alpha$ | ratio of disposed item, $(0 < \alpha < \beta)$ |
| $d$ | demand |

Firstly, it is supposed that the system delivers a constant demand $d$ to the market. The used products are recovered from the market and delivered to the repairable product store. An amount $\alpha d$ is disposed items, while the rest of the recovered items, i.e. the amount $\beta_\zeta d$, is remanufactured and transferred to finished product store. In order to meet the required demand, the amount $(1-\beta_\zeta)d$ must be manufactured. In classic models, there are no restrictions on remanufacturing and a proportion $\beta$ is remanufactured (remanufacturing rate) and the proportion $(1-\beta)$ is disposed (disposal rate). Hence, $\beta$ and $\beta_\zeta$ are identical in that case. Whereas limited remanufacturing is modeled by defining the variable $\zeta$, which denotes the number of times an item is remanufactured and they assume that a product can only be remanufactured for $\zeta$ times. The basic model with the used variables for production and remanufacturing system is presented in Figure 1, which is adapted from El Saadany et al., (2013).



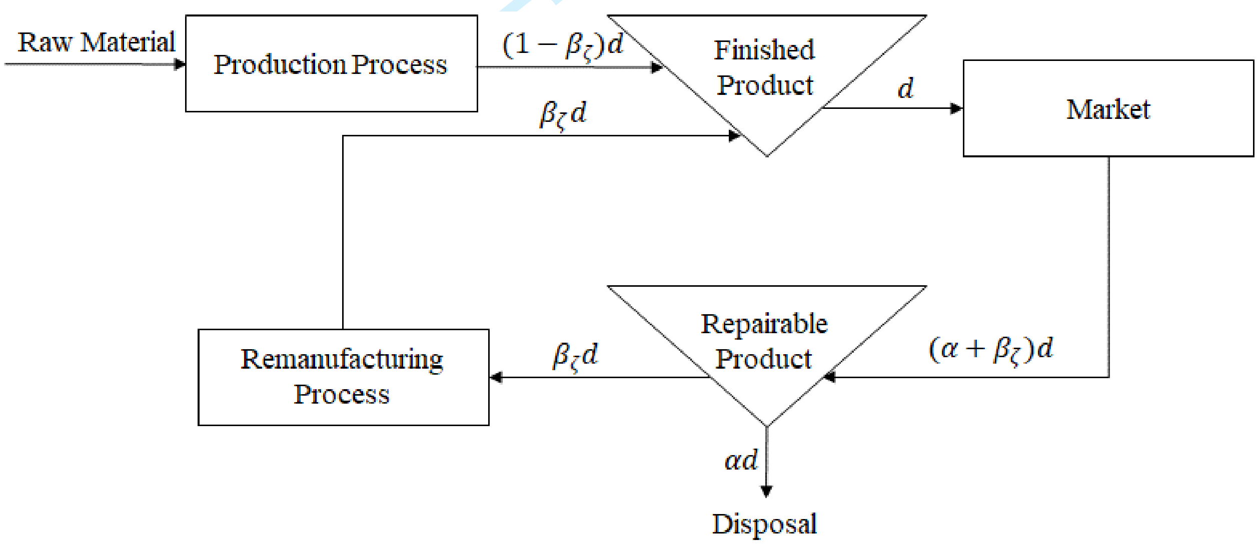



*Figure 1 – Material flow of a single item for production and remanufacturing system*

### *3.2.2. The model of Teunter (2001)*

The effects of remanufacturability are examined on the basis of the model of Teunter (2001) as the second model. This model is an extension of the classic EOQ model for recovery systems by Schrady (1967). In addition to this model, they defines different holding costs such as holding cost per manufactured item ($h_m$), holding cost per remanufactured item ($h_r$) and different unit costs such as unit cost of manufacturing per item ($c_m$), unit cost of remanufacturing per item ($c_r$), disposal cost per item ($c_d$) for holding newly manufactured items and remanufactured items. Teunter (2001) argues that remanufactured products actually have not the same quality as new items but still ignored quality affect in the formulation and the remanufacturing cost is usually lower than manufacturing costs. Therefore, the holding costs, which are mainly opportunity cost, are lower for recovered items. By contrast to the model of Schrady (1967), Teunter (2001) examines a sequence of $R$ remanufacturing cycles with lot size $Q_r$ and M manufacturing cycles with lot size $Q_m$. The systems serve a market with demand rate $d$. The lots are manufactured and remanufactured at infinite rate, i.e. whenever a lot is produced, the respective lot size is added instantaneously to the finished product store. After this, the finished product store empties with demand rate $d$.

After introduced two significant papers that form the basis of our study, the differences of this study can be emphasized in terms of two aspects:

i. El Saadany et al., (2013) just focused on predicting the number of remanufacturing times by performing numerical analysis instead of finding an optimal number of remanufacturing such as when $\zeta$=1, 2,3, and $\infty$. Meanwhile, Teunter (2001) tried to find lot size by minimizing total cost formulation includes variable cost, fixed cost, unit cost and disposal cost. However, their study did not tackle the addressed problem as a discovery of the optimal number of remanufacturing times. On the other hand, El Saadany et al., (2013) determined remanufacturing, production and disposal amount in the following tables seen in Table 2 in every period when a product is recovered once ($\zeta$=1), twice ($\zeta$=2) and three times ($\zeta$=3).
ii. The main point is that they assumed $\beta$ ratio always same and a value between $0 < \beta < 1$. However, $\beta$ value does not always have to be the same. Because of the seasonality or economic fluctuations, $\beta$ value could be variable and even it can be defined as a linear or nonlinear function instead of a specific value. At this stage, $\beta$ value is taken as a linear equation within the scope of this study by finding the amount of products which are collected from outside to recover process.

*Table 2: Remanufacturing, production and disposal amount in every period when a product is recovered once (**ζ=1**), twice (**ζ=2**) and three times (**ζ=3**).*

| **ζ=0** | |
|---|---|
| **Production** | |
| **Age** | **Amount** |
| 0 | d |
| 1 | 0 |
| 2 | 0 |
| Disposed | |

| **ζ=1** | | **ζ=1** | |
|---|---|---|---|
| **Remanufacturing** | | **Production** | |
| **Age** | **Amount** | **Age** | **Amount** |
| 0 | | 0 | *(1-β)d* |
| 1 | *βd* | 1 | *βd* |
| 2 | *0* | 2 | *0* |
| Disposed | *(1-β)d* | Disposed | |

| **ζ=2** | | **ζ=2** | |
|---|---|---|---|
| **Remanufacturing** | | **Production** | |
| **Age** | **Amount** | **Age** | **Amount** |
| 0 | | 0 | *(1-β)d* |
| 1 | *β(1-β)d* | 1 | *β(1-β)d* |
| 2 | $\beta^2 d$ | 2 | $\beta^2 d$ |
| Disposed | *(1-β)d* | Disposed | |

| **ζ=3** | | **ζ=3** | |
|---|---|---|---|
| **Remanufacturing** | | **Production** | |
| **Age** | **Amount** | **Age** | **Amount** |
| 0 | | 0 | $(1-\beta+\beta^3)d$ |
| 1 | *β(1-β)d* | 1 | *β(1-β)d* |
| 2 | $\beta^2(1-\beta)d$ | 2 | $\beta^2(1-\beta)d$ |
| Disposed | $(1-\beta+\beta^3)d$ | Disposed | |



### *3.3. Decision model formulation*

Total cost minimization will be achieved by finding the optimal number of remanufacturing times which should be determined by minimizing the unit cost instead of the total cost, as total cost will increase when remanufacturing occurs. At the point, where unit cost is minimized, the number of remanufacturing times could be calculated as a dependent variable while the independent variables to be used in the calculations are setup cost, holding cost, disposal rate, and production quantity. For this model, the notations used throughout the paper are listed in Table 3 as follows:

*Table 3 - Notation of proposed model*

| *Symbol* | *Explanation* |
|---|---|
| $D$ | demand |
| $S_m$ | manufacturing setup cost |
| $S_r$ | remanufacturing setup cost |

| | |
|---|---|
| $V_m$ | manufacturing variable cost |
| $V_r$ | remanufacturing variable cost |
| $\beta_\varsigma$ | remanufacturing rate at the time $\zeta$ |
| $\beta$ | remanufacturing rate |
| $a$ | coefficient of the regression equation |
| $b$ | constant value |
| $x$ | number of remanufacturing |
| $\zeta$ | number of times an item can be remanufactured |

In this model some limitations are available are listed below:

i. The glass, metal, or aluminium products are not selected to remanufacture as their raw metals can be recycled by an infinite number of times.
ii. Although different demand alternatives are analysed in simulation part, however, demand is constant for each scenario.
iii. Cost parameters for both remanufacturing and manufacturing are collected under two headings: setup cost and variable cost. Meaning that, other cost parameters such as holding cost, ordering cost, and transportation cost are not considered specifically.
iv. In this study, '$\beta$' value the amount of products which are collected from outside to remanufacture is taken as a linear equation.

Because the optimal number of remanufacturing times will be calculated based on the point where the unit cost is minimized, in the objective function of the unit cost equation, the number of remanufacturing times should be a dependent variable as defined before. Furthermore, there is a need to establish a relationship between the other parameters establishing the unit cost equation such as fixed costs, variable costs, demand and remanufacturing rate with the number of remanufacturing times. The fixed cost is directly related to production rate and remanufacturing rate in the unit cost equation will be divided by total demand whereas variable costs are multiplied by the production and the remanufacturing rate since the variable costs will be associated with the remanufacturing rate. When the relationship between the remanufacturing rate and the number of remanufacturing times is established, the optimal number of remanufacturing times could be possible to calculate. In the study, it is assumed that there will be a linear relationship (e.g. $y = ax + b$) between these two parameters, as seen in equation (1). When the number of remanufacturing ($\varsigma$) and the coefficient of the regression equation ($a$) are multiplied and summed up with a constant value ($b$), the remanufacturing rate ($\beta_\varsigma$) is obtained.

$$\beta_\varsigma = a\varsigma + b \tag{1}$$

The formula of the unit cost to be used as the objective function in cost optimization is shown in equation 2. The unit cost is equal to the total of unit manufacturing setup cost, unit remanufacturing setup cost, unit manufacturing variable cost and unit remanufacturing variable cost. The unit manufacturing setup cost is calculated by calculating the ratio of the manufacturing setup cost ($S_m$) to the total production quantity, the ratio of waste to product ($1 - \beta_\varsigma$) and the demand ($D$). The unit remanufacturing setup cost is calculated by calculating the ratio of the remanufacturing setup cost ($S_r$) to the multiplication of demand and the remanufacturing rate, which is the total remanufacturing quantity. The unit manufacturing variable cost is equal to the manufacturing variable cost ($V_m$) multiplied by the waste rate. The unit remanufacturing variable cost ($V_r$) is the product of the unit remanufacturing variable cost and the remanufacturing rate.

$$\frac{S_m}{(1-\beta_\varsigma)D} + \frac{S_r}{\beta_\varsigma D} + V_m(1-\beta_\varsigma) + V_r\beta_\varsigma \tag{2}$$

The equation above represents the unit cost formulation by taking into setup cost and variable cost account for both manufacturing and remanufacturing process. However, a constraint should be inserted into mathematical formulation given in equation 3. The reason behind this constraint is that remanufacturing unit cost must be less than manufacturing unit cost. The cost of manufacturing is always available regardless of whether remanufacturing process occur or not. In order to take remanufacturing decision of any product, the unit cost of remanufacturing should not exceed the cost of production cost.

$$S_m + V_mD \geq S_m + S_r + V_m(1-\beta_\varsigma)D + V_r\beta_\varsigma D \tag{3}$$

From equation 4 to equation 8, the constraint given in equation 3 is rearranged systematically.

$$S_m + V_m D - S_m - S_r - V_m(1 - \beta_\varsigma)D - V_r\beta_\varsigma D \geq 0 \quad (4)$$

$$+V_m D - V_m(1 - \beta_\varsigma)D - V_r\beta_\varsigma D - S_r \geq 0 \quad (5)$$

$$V_m\beta_\varsigma D - V_r\beta_\varsigma D - S_r \geq 0 \quad (6)$$

$$\beta_\varsigma D(V_m - V_r) - S_r \geq 0 \quad (7)$$

$$S_r \leq (V_m - V_r)(a\varsigma + b)D \quad (8)$$

In order to calculate the optimal remanufacturing times, the point must be found, where the derivative of the equation according to the number of years is equal to 0 given in equation 9.

$$\frac{d}{dx}\left(\frac{S_m}{(1-(ax+b))D} + \frac{S_r}{(ax+b)D} + V_m(1-(a\varsigma+b)) + V_r(a\varsigma+b)\right) = 0 \quad (9)$$

When the constraint given in equation 3 is written in the unit cost given in equation 2, the formula given in equation 10 is obtained.

$$\frac{d}{dx}\left(\frac{S_m}{(1-(ax+b))D} + \frac{(V_m - V_r)(ax+b)D}{(ax+b)D} + V_m(1-(a\varsigma+b)) + V_r(a\varsigma+b)\right) = 0 \quad (10)$$

When the derivative of the formula given in equation 10 is taken according to the number of remanufacturing times, the formula given in equation 11 is obtained.

$$\frac{aS_m}{(1-(a\varsigma+b))^2 D} + a(V_r - V_m) = 0 \quad (11)$$

When the formula given in equation 11 is multiplied by the ratio of the demand $(\frac{D}{a})$ to variable $(a)$, the formula given in equation 12 is obtained.

$$\frac{S_m}{(1-(a\varsigma+b))^2} + D(V_r - V_m) = 0$$
(12)

When the denominators in equation 12 are eliminated, the formula is as given in equation 13.

$$S_m + D(V_r - V_m)(a^2\varsigma^2 + 2ab\varsigma - 2a\varsigma + b^2 - 2b + 1) = 0 \quad (13)$$

Equation 13 is an example of second order polynomial equation, that is mean there are two roots ($\varsigma_1$ , $\varsigma_2$) available when the equation solved. The root having minimum positive value is the real solution of equation.

### *3.4. Solution approach*

Figure 2 presents a flowchart that illustrates the aforementioned proposed decision model with steps. In the first step (figure out linear relation), the time-dependent change of disposal rate is modelled linearly. In the second step, the maximum number of remanufacturing times ($t_{max}$) is calculated to determine whether the solution that the model will produce is feasible. In the third step, values respectively for the average demand ($D$), remanufacturing setup cost ($S_r$), remanufacturing variable cost ($V_r$) and manufacturing variable cost ($V_m$) are assigned. In the fourth step, the optimal number of remanufacturing times ($N_r^*$ ) is calculated using the equation proved in the study. If the optimal number of remanufacturing times is greater than$t_{max}$, the result is set to 0 because the solution found is infeasible, so remanufacturing should not be performed seen in fifth step. If the value found is less than the calculated product life cycle, it is optimal to remanufacturing the value obtained seen in sixth step. Furthermore, the pseudo code of this decision model is illustrated in Table 4.

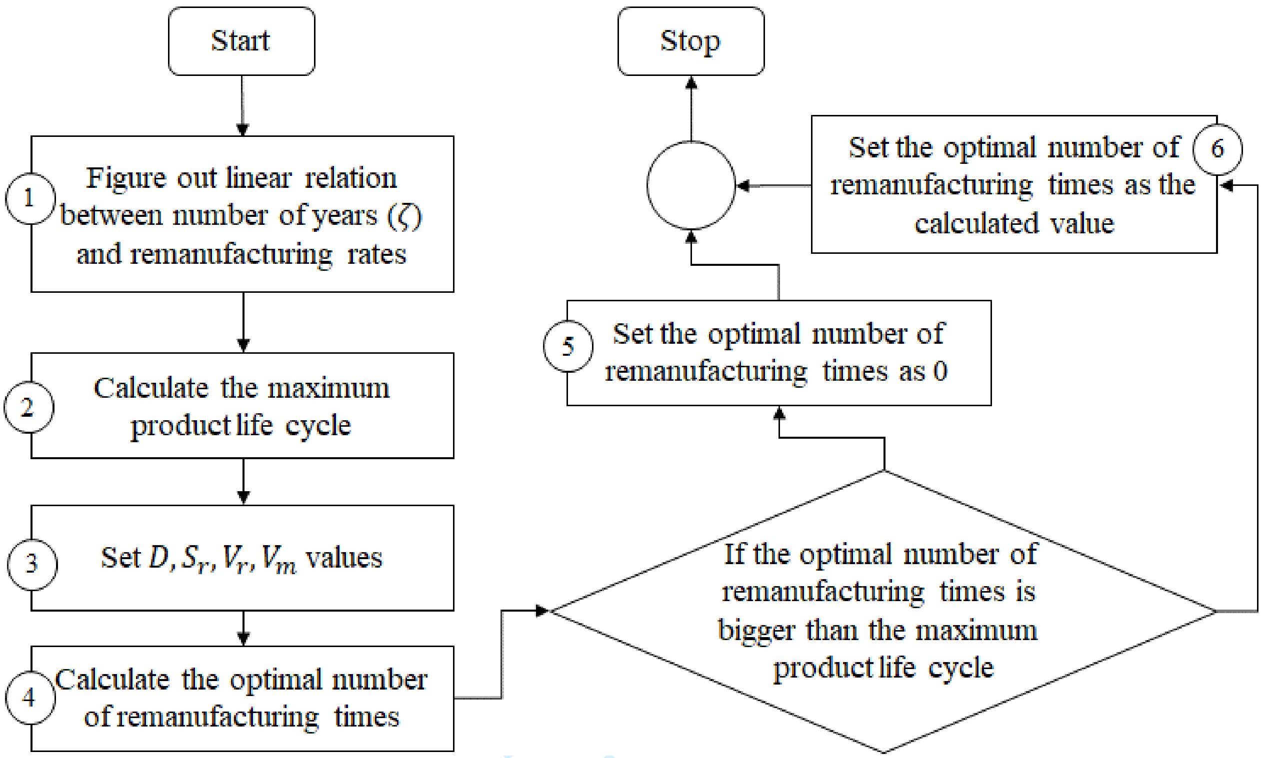



*Figure 2- Flowchart of solution approach*

*Table 4 - Pseudo code of proposed decision model*

1. Procedure OptimalNumberOfRemanufacturingTimes ($\beta_\varsigma$, $\zeta$)
2. $a,b =$ CalculateRegressionEquation ($x = \zeta$, $y = \beta_\varsigma$)
3. Set $t_{max}$, as the maximum product life cycle
4. Set demand ($D$), setup cost of remanufacturing ($S_r$), variable cost of remanufacturing ($V_r$), variable cost of manufacturing ($V_m$)
5. $x_1, x_2 =$ roots( $S_m + D(V_r - V_m)(\mathrm{a}^2\varsigma^2 + 2\mathrm{ab}\varsigma - 2\mathrm{a}\varsigma + \mathrm{b}^2 - 2\mathrm{b} + 1)$)
6. If $x_1 < 0$ Then
7. Set $\varsigma_1 = t_{max} + 1$
8. End If
9. If $x_2 < 0$ Then
10. Set $\varsigma_2 = t_{max} + 1$
11. End If
12. $N_r^* = \min(\varsigma_1, \varsigma_2)$
13. If $N_r^* > t_{max}$ Then
14. Set $N_r^* = 0$
15. End If
16. return $N_r^*$

## 4. Analysis and Simulation Experiment

According to world trade statistical review report of World Trade Organization (WTO, 2018), the chemical products are the most exported products after petroleum and mining products. Hence, there has been an increasing interest in remanufacturing in the chemical industry, including the plastics industry, which provides also cost advantages to companies. At this point, automobile components (dashboard, instrument panels, rigid profiles), construction elements (profiles, hoses, cables, flooring) or other commercial products (artificial leather, conveyor belts) which are PVC based products are chosen as an example of remanufacturing products within the scope of this study. The reason behind selection of pre-mentioned products is PVC has a limited number of remanufacturing cycles.

In order to measure the behaviour of the developing decision model under different cost and demand conditions, a simulation system was developed using Java software language. Simulation scenarios were created by taking into account the parameters of demand, manufacturing setup cost, remanufacturing setup cost, manufacturing variable cost and remanufacturing variable cost. The results of simulation scenarios were further analysed using Java software toolkit. The ranges of values and increments of these parameters are given in Table 5. The number of simulation scenarios was calculated by applying the difference of ranges divided by increments per parameter, equals to 2.250.000. The parameters of the simulation scenarios were further determined (Cesur, 2019). The parameters used in the thesis study were collected from articles (Carvalho and Nascimento, 2016; Cunha and Melo, 2016; Sifaleras and Konstantaras, 2017), which are noted the importance of manufacturing cost, inventory holding cost, transfer cost, fixed cost and remanufacturing cost for planning. Apart from the specified parameters, the estimated product life cycle of PVC is taken from the report of "Mechanical Recycling of PVC Wastes" published by the European Commission (EC, 2000) is determined as 50 years, while a and b parameters specified in the model take -0.02 and 1 values.

*Table 5 - Parameters with range and increment values*

| *Parameter* | *Range* | *Increment* |
|---|---|---|
| Demand ($\boldsymbol{D}$) | 1000-25000 | 1000 |

| | | |
|---|---|---|
| Manufacturing Setup Cost ($\boldsymbol{S_m}$) | 5000-100000 | 5000 |
| Remanufacturing Setup Cost ($\boldsymbol{S_r}$) | 5000-100000 | 5000 |
| Manufacturing Variable Cost ($\boldsymbol{V_m}$) | 20-90 | 5 |
| Remanufacturing Variable Cost ($\boldsymbol{V_r}$) | 20-90 | 5 |

## 5. Results and Discussion

### *5.1. Scenario-based and Parameter Effect Analysis*

In this section, the five parameters given above are analysed in terms of scenario-based and parameter effect analysis to determine their effects on the optimal remanufacturing times (ORT). Apart from other studies, not only one value of pre-determined parameters is investigated, a range of values are simulated and analysed comprehensively.

#### *5.1.1. Effect of Demand*

The ORT occurs in all combinations of manufacturing setup cost ($S_m$), remanufacturing setup cost ($S_r$), remanufacturing variable cost ($V_r$), manufacturing variable cost ($V_m$) are averaged, while demand ($D$) ranges from 1000 to 25000. The reason for this is to observe the general mass trend. When the trend is analysed, similar remanufacturing characteristics are seen in demands of 7000 which is always decreasing above as shown in Figure 3. ORT ranges from 7 to 10 years, while average demand shortens when demand exceeds 7000. While demand is low, the gain from $V_m - V_r$ cannot handle the remanufacturing setup cost, so that few scenarios can also be remanufactured, thus the year of optimal remanufacturing is low. When this situation in low demand is ignored, it is understood that the change in demand does not cause much change between ORT. When the correlation between demand and ORT is examined ($r = -0.15$), it is found that the correlation is close to 0.

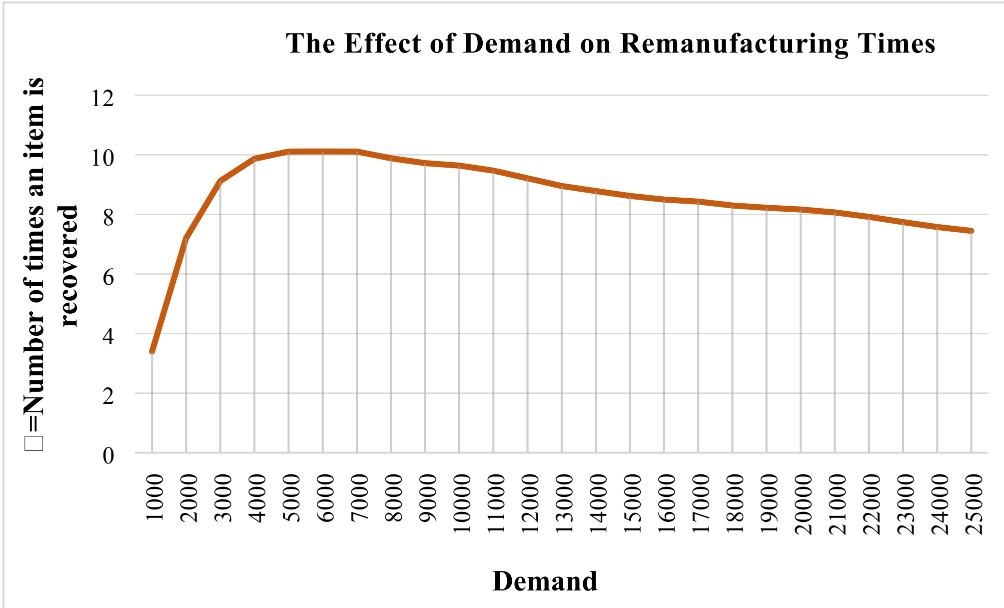



*Figure 3 – The effect of demand on optimal remanufacturing times*

### *5.1.2. Effect of Cost*

The effect of cost is considered in terms of setup cost and variable cost. Since production would be more advantageous than remanufacturing while the manufacturing setup cost ($S_m$) were low, ORT is less. However, when it reaches a certain level (like more than 70000), the effect of $S_m$ disappears and is fixed in the simulation for an average of 9 years. In Figure 4, the general behaviour of $S_m$ is observed.

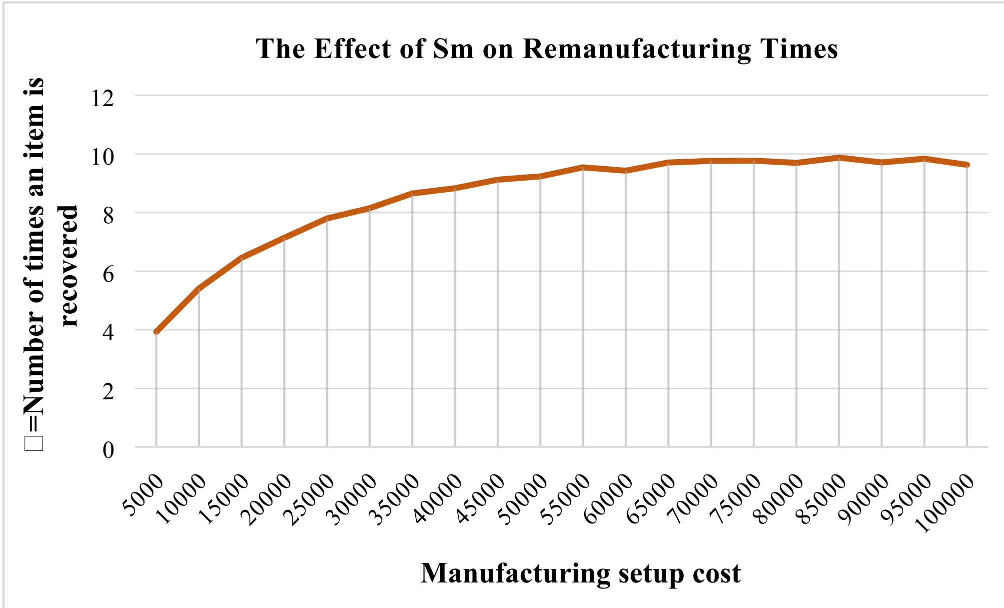



*Figure 4 – The effect of manufacturing setup cost on optimal remanufacturing times*

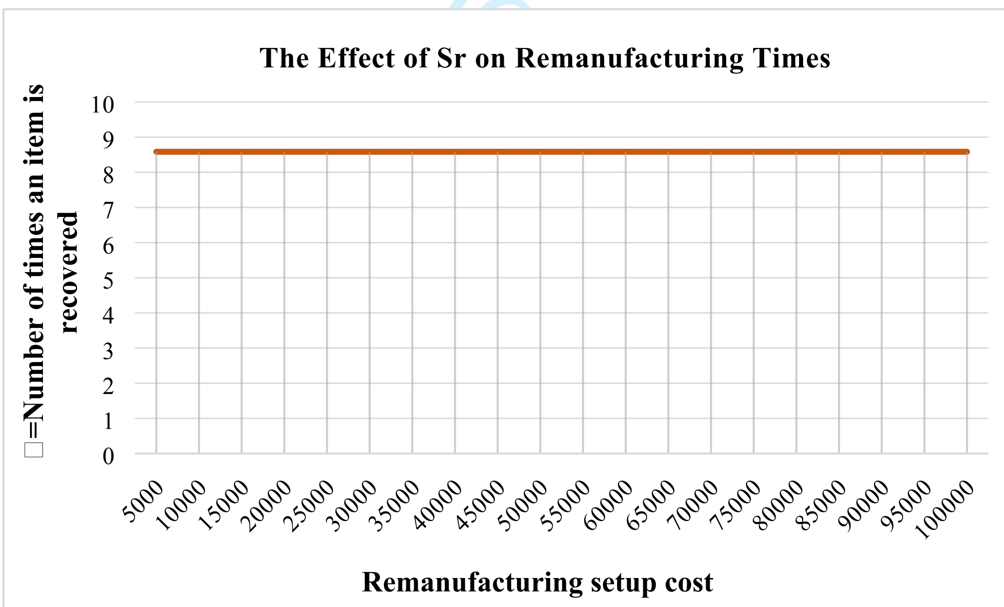
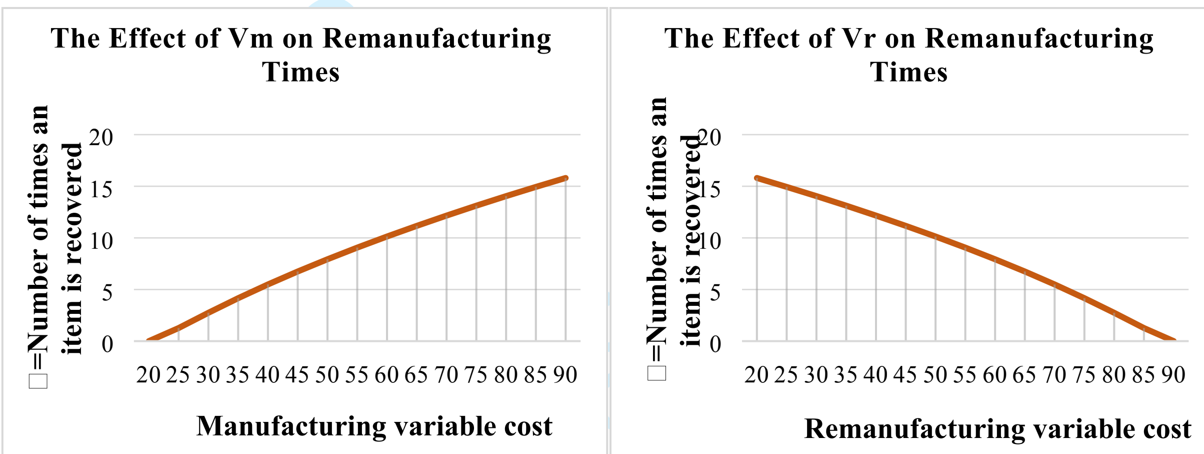



*Figure 5 – The effect of remanufacturing setup cost on optimal remanufacturing times*

With the constraint added in equation 9, $S_r$ is out of the formula as shown in equation 10, and it is shown in the Figure 5 below that there is no effect on ORT. Setup remanufacturing is directly related to whether remanufacture or not however, there is no significant relationship between remanufacturing set up cost and ORT after taking decision to remanufacture

Manufacturing variable cost and remanufacturing variable cost have a direct impact on ORT. When this effect was measured by correlation, the strength of the relationship between $V_m$ and ORT was $r = 0.9965$, whereas the relationship between $V_r$ and ORT was $r = -0.9965$. The inverse ratio between the correlation values found in Figure 6 led to the symmetrical effects of $V_m$ and $V_r$ on ORT.




(a) (b)

*Figure 6 - The effect of a) Manufacturing variable cost and b) Remanufacturing variable cost on optimal remanufacturing times*

The effect of $V_m$ and $V_r$ on ORT is not directly from $V_m$ and $V_r$, but from the difference $V_m - V_r$ given in equation 8. In cases, where the multiplication of remanufacturing rate with $V_m - V_r$ is smaller than $S_r$, the likelihood deteriorates because the constraint given in equation 8 is not provided. In the first 15 dataset, where the difference of $V_m - V_r$ is less than 0, ORT is 0 is shown in Figure 7. When the difference is more than 15, breakeven point appears. The reason for this fracture is the point where $V_m - V_r$ crosses $S_r$.

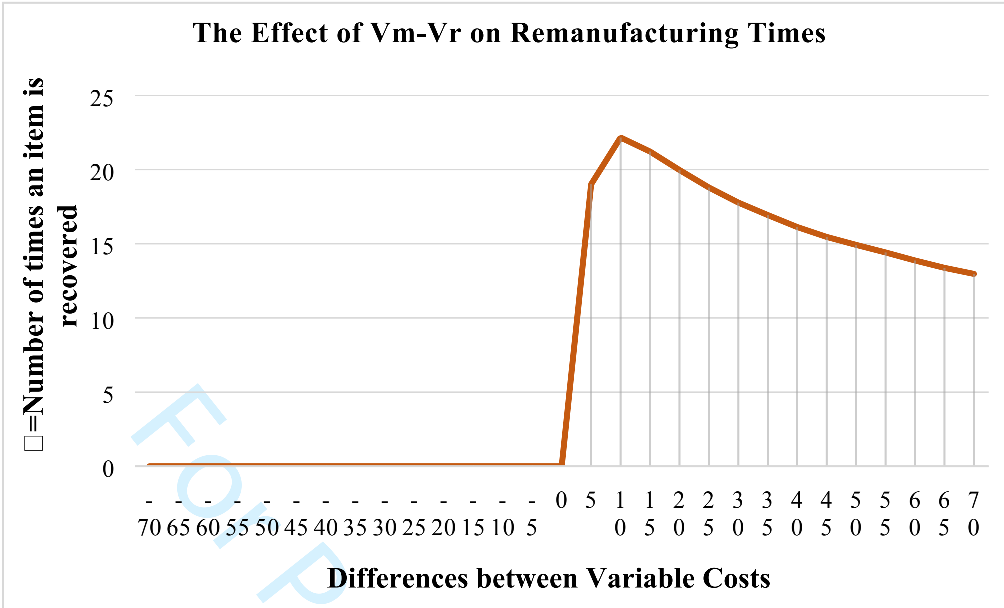



*Figure 7- The effect of Vm - Vr cost on optimal remanufacturing times*

## 5.2. Unique Contributions and Managerial Implications

There has been a little consideration in the literature about remanufacturing, which aim to find the number of remanufacturing times for resource management on a circular economy platform. The available literature has some limited scope and assumptions. For instance, offered models do not provide an optimal number of remanufacturing times directly, although aim of such studies is to find out it. Also, they took just some product types manufactured with metals that have an infinite number of remanufacturing times. Specifically, two fundamental studies 1) El Saadany et al., (2013) just utilised numerical analysis by changing remanufacturing times such as when $\zeta$=1, 2,3, and $\infty$ in attempt to predict the minimum total cost and 2) Teunter (2001) tried to find lot size by considering variable cost, fixed cost, unit cost and disposal ı. However, neither studies handle the problem as a discovery of the optimal number of remanufacturing times. In this study, the optimal number of remanufacturing times is calculated based on the point where the unit cost is minimised. When past studies are compared with this study, it is apparent to realise that total minimum cost at the point of optimal remanufacturing times was not provided in their model until now. They did only by brute force (trial-and-error) analyses. Besides that, it is known that minimum cost ensures less raw material consumption, a reduced amount of manpower usage, less time, money and energy wastage in other words it increase total resource efficiency.

**6. Conclusion**

When calculating optimal number of remanufacturing times – demand, manufacturing setup cost, remanufacturing setup cost, manufacturing variable cost and remanufacturing variable cost are considered. Therefore, the model focuses on the profitability of the investment. The optimal number of remanufacturing times obtained in the model are the maximum product age that remanufacturing is profitable, which is answer of the first research question.

Significant characteristics that differentiate the proposed decision model from the other models include: (i) This model calculates optimal number of remanufacturing times directly to ensure maximum profitability, whereas the presented models in Teunter (2001) and El-Saadany et al., (2013)'s work calculate the optimal remanufacturing times only by brute force (trial-and-error). (ii) The remanufacturing rate ($\beta$) is not a fixed value, but a parameter expressed by a linear function, which is also the answer of the second research question.

The answer of the third research question can be summarized that the difference between variable costs of manufacturing and remanufacturing, demand, and setup cost of remanufacturing determine the optimal number of remanufacturing times directly, whereas setup cost of manufacturing has no any impact on it. Besides, doing remanufacturing process does not seem to make sense, if demand does not exceed a specific point. Further, it is concluded that any product can only be remanufactured a finite number of times before it is no longer economically feasible or practical to do so. At that point, it should be replaced with a newly manufactured product. In fact, in many cases, manufacturing and remanufacturing are mutually beneficial for companies to earn more profit.

The results of this study could be extended in the future by incorporating following cases: the remanufacturing rate ($\beta$) can be rendered as non-linear and the decision model can be expressed more accurately and flexibly. When calculating optimal remanufacturing times, the time value of money can also be expressed in future work.

Within the scope of this study, firstly, a mathematical model is proposed to find an optimal remanufacturing times and parameters of the model are analysed by doing simulation experiments.

As a future research in terms of methodological feature, the sensitivity analysis could be inserted to find a suitable range for each parameter. Thus, model would be used as a decision support system for managers considering behavior of parameters. When remanufacturing is assessing from the point of environmental aspect, it is so clear that remanufacturing causes less consumption not only in raw material but also total energy in production line. Besides that, knowing how many times a product will be remanufactured at most it could be possible to find the optimum point of total resource consumption such as transportation, raw material, manpower and energy. Further, the objective function of the proposed mathematical model ensures minimum unit cost by finding optimal number of remanufacturing times. At this point, it is obvious that firms can decrease prices in order to compete with other competitors in the market when they are aware of the minimum unit cost. The total demand practically increases just because they broaden their market share. Thereby, it brings about an enhanced social welfare since both companies and users are placed well in the market.

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