Int J Adv Manuf Technol (2015) 77:1767–1779
DOI 10.1007/s00170-014-6509-9

ORIGINAL ARTICLE

Reverse supply chain plan for remanufacturing commercial returns

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Received: 28 March 2014 / Accepted: 16 October 2014 / Published online: 19 November 2014

Abstract The flow of commercial returns, products returned by customers for any reason within 90 days of sale, is a significant concern for many manufacturers. The total value of these returns is estimated at about $100 billion a year in the USA. In order to reduce their negative impacts on the environment and prevent high disposal costs, these returned products need to be properly handled, processed, and, if applicable, remanufactured, recycled, or reused. However, since the primary focus of most manufacturers is the forward supply chain, a large proportion of the returned products' value is lost. Two key decision policies affecting the performance of such systems are the target quality for components used in the primary product and duration of the time returned products are accumulated before they are remanufactured. High targeted quality increases the production cost but cuts on product return rate. Long accumulation time, on the other hand, increases production lot sizes for remanufacturing that results lower remanufacturing costs per unit product. When there is a market for remanufactured products the tradeoff between profit from selling primary products and that of remanufactured units may justify targeting a lower than perfect quality and still maximize the total profit. And this could be achieved without negative effects on environment. In this work, a model for a forward/reverse supply chain is developed to satisfy a fixed demand with a combination of new and remanufactured products. The objective is to maximize the total profit as a function of two above decision factors. The application of the proposed model has been demonstrated by several numerical examples.

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Keywords Remanufacturing · Returned products · Optimization · Sustainability · Reverse supply chain

1 Introduction

Nowadays, in order to attract customers in a highly competitive marketplace, most mass merchandisers offer full refunds within 15–90 days of purchase—no questions asked. As a result, the return rates from consumers to manufacturers or retailers are usually high. The percentages of products that are returned can range from 11 to 20 % for consumer electronics and up to 35 % for high fashion apparel [1]. The value of products that US consumers return to retailers exceeds $100 billion each year [2]. Just in the electronics industry, around $13.8 billion was spent in 2007 to repackage, restock, and resell returned products [3].

In the traditional supply chain models, the impact of returned products is always ignored [4]. However, manufacturing products with perfect quality, i.e., 100 % free of defective parts, necessitates very high quality standards with exceedingly high production costs. Aiming for that quality does not necessarily achieve the desirable goals of satisfying costumers and affordability. Especially with the amazingly lenient return policies that nowadays almost all the manufacturers have for their products, even perfect products may be returned.

Therefore, as the volume of products flowing back from customers increases, handling customer returns has become critical. Serious consideration should be taken into account to design the optimum reverse supply chain to minimize the cost of dealing with returned products. In this study, we investigate the effect of two decision policies on the performance of a manufacturing/remanufacturing system and develop a model for maximization of the total profit as a function of these policies. These policies involve the decision on the target quality of parts used to manufacture primary products and the duration of the time to accumulate returned products before they are remanufactured and sold as aftermarket units.

Targeting high standards for manufacturing primary products increases the production costs but results in a lower product return rate. High production costs clearly have a negative impact on total profits. On the other hand, low return rates favor profitability because they cut the cost of refunds, repair, and disposal or remanufacturing of returned products. However, if there is a market for aftermarket products, some level of return rate may lower production costs for primary products and have a positive effect as well on aftermarket products sales because they provide the input for the reverse supply chain for remanufacturing. This concept leads to the notion that targeting the highest possible quality for primary products may not necessarily be the best decision for maximizing profitability. Furthermore, if the returned products are remanufactured the environmental impact of disposing defective products would be minimized.

The second policy factor, the duration of accumulation time, affects profitability in a different way. Its major impact is on economy of scale for remanufacturing returned products. Longer accumulation times result in larger lot sizes for remanufacturing which often causes a reduction in the unit cost for remanufactured products. At the same time, keeping returned products has a negative impact on the net profit due to loss of value that products suffer while waiting. Thus, it becomes clear that interaction between the targeted quality and accumulation time of returned products have a major role in planning and optimizing the reverse supply chain for a manufacturing/remanufacturing system.

Focusing primarily on the forward supply chain management usually results in losing a large proportion of the returned product value. Although cost-efficient logistics processes may be desirable for collection and disposal of products when return rates are low, this approach can actually limit a firm's profitability in today's business environment. The design of reverse supply chains only based on cost efficiency can create time delays that limit the options available for reusing the returned products, which can lead to substantial losses in product value recovery. This is especially true for shortlife—period time—sensitive products where these losses can exceed 30 % of the product value. Time-sensitive, consumer electronics products such as PCs can lose their values at rates in excess of 1 % per week. On the other hand, a returned disposable camera body or a power tool has a lower marginal value of time; the cost of delay is usually closer to 1 % per month [5]. Therefore, the need for designing the optimum reverse supply chain to prevent these losses is necessary.

As stated above, this study suggests a model to find the optimum quality of parts to target in manufacturing primary products and the optimum accumulation time before remanufacturing the returned products. The objective is to maximize the overall profit from selling a combination of primary and remanufactured products. Several considerations should be taken into account:

- In this study, the quality is defined as the probability of a product being defective. This probability could be similarly defined as the defective rate for a lot of the product being produced. Targeting for higher quality will result in lower defective rates, but will increase manufacturing cost. The quality of the product, as will be explained later in the paper, is estimated from the quality of parts or components used in the product
- Although accepting some level of defective rate may reduce production costs, it will also result in an increase in commercial return rate. If returned products are sent to a return center and are repackaged and/or remanufactured, an increase in return rate will result in an increase in shipping, repackaging, and remanufacturing costs and therefore a decrease in total profit.
- Increasing the accumulation time before handling the returned products in the return center will result in remanufacturing of larger batches of returned products. Typically remanufacturing costs is a decreasing function of the batch size. Therefore, the longer the accumulation time, the less expensive it would be to remanufacture the returned products. However, too long accumulation times will result in losing the value of the returned products because of the cost of capital invested in products, decay, and obsoleteness as well as increasing storage and inventory-carrying costs.

Clearly, this model is not recommended for every product and manufacturer. The proposed model is designed for manufacturing systems in which

- The production cost is inversely proportional to the quality (defective rate) of parts used to manufacture primary products.
- The total demand is satisfied by a combination of the primary and remanufactured products.
- The discount provided for remanufactured products is such that it makes it indifferent for a costumer to buy either.
- Every returned product is sent to return center, and the retailer do not sell a returned product. This is mostly the case for well-known manufacturers such as Hewlett–Packard Company (HP) and Bosch.

Several numerical examples have been examined to investigate the application of this model in different cases. It was established that for every demand, there is a specific optimum value for production quality and a range of optimum accumulation times. It is expected that this research will open several new avenues for looking at the targeted design quality from different perspectives.

The paper is organized as follows: Section 2 presents a review of literature in related areas. Section 3 provides the details of the presented model. Numerical examples are discussed in Section 4. Finally, Section 5 outlines conclusions and future research plans.

2 Literature review

Most of the companies currently involved in manufacturing and marketing of products have been incorporating reverse logistics in their supply chain planning as a way of complying with environmental regulations and sustainability expectations, as well as gaining a business advantage from the recovered products. Although reverse logistics is relatively a new term, initial attempts to address the inventory of remanufactured items or products date back to the 1960s, with Schrady [6] being the first to investigate a repair-inventory system.

In today's world with the high costs of disposal of returned products, there has been an increasing attention on the reverse supply chain. This literature review is comprised of three parts: reverse supply chain for end of life products, reverse supply chain for commercial returns, and false failure returns.

2.1 Reverse supply chain for end of life products

There have been numerous research works on closed loop supply chain, focusing on remanufacturing the end-of-life (EOL) products. However, there has been little research on how to design the reverse supply chain specifically for commercial product returns. Remanufacturing, reverse logistics, and closed loop supply chain of EOL returned products have been widely studied [7–9]. These studies focused on cost-efficient recovery of EOL products and meeting environmental standards such as disposal limits and costs.

El Saadany et al. [10] developed a model to consider the optimum production, remanufacturing and disposal costs where a manufacturer serves a stationary demand by producing new items of a product, as well as by remanufacturing collected used and returned items. The model intends to help in determining whether to go for remanufacturing or choose disposal by calculating the remanufacturing cost, which includes the cost involved in collecting the used items and bringing them back to the market. Roy et al. [11] took production and recycling rates as decision variables with stock-dependent demand and demand-dependent imprecise return rate. This imprecise production–inventory system was solved using fuzzy differential equations.

By extending previous research works to model a more complete recycling network, Dat et al. [12] minimized the total costs involved in the recycling process for a case where various treatment sites processed multiple types of waste in electrical and electronic products. The proposed model considers four stages of the recycling process consisting of collection sites, disassembly sites, treatment sites (recycling facility and repair facility), and final sites (disposal facility, secondary market, primary market).

2.2 Reverse supply chain for commercial returns

The works mentioned above have been developed for recycling EOL products. However, with the increasing rate of commercial returns, recently, some researchers developed several models to deal with these systems. Focusing on the time value of money, Blackburn et al. [5] suggest that significant monetary values can be gained by redesigning the reverse supply chain to reduce costly time delays. Based on their research, these savings are higher in fast clockspeed industry such as consumer electronics, as opposed to a slow clockspeed industry such as power tools. By again focusing on the same decision variable, time value of money, Guide et al. [1] presented a model for a single retailer and return center. They concluded that a 1-day reduction in travel time between different facilities in the returns network would result in a profit of $35,069 when the reduction takes place between the evaluating facility and distributor. The savings were $93,797, $72,475, and $79,489 when the travel time was cut by 1 day between the customer and evaluating facility, evaluating facility and remanufacturing, and remanufacturing and the secondary market, respectively.

Azadivar et al. [13] focused on production volumes that justify remanufacturing. Several operation parameters were considered in their model such as defective rates of the original parts, cost of disposal of returned products, discount for aftermarket units, and so on.

Another factor that has been investigated in the published research is the impact of targeted quality of parts used to manufacture primary products. Masoud et al. [14] developed a model to investigate the impact of the targeted quality and the primary production rate on a stochastic profit function. This model was then optimized to provide the desired quality to target and the number of primary products to manufacture to maximize the profit.

2.3 False failure returns

As a result of offering liberal return policies, many consumers have grown accustomed to being able to bring the purchased products back to the store for just about any reason. For example, in the electronic industry in the USA, a large proportion of these returns are due to reasons other than functional defects in the products [3]. This category of returns is called "false failure returns." The cost of a false failure return includes the processing actions of testing, refurbishing if necessary, repackaging, the loss in value during the time the product spends in the reverse supply chain (a time that can exceed several months for many firms), and the loss in revenue because the product is sold at a discounted price [15].

3 The model

The model breaks down the demand cycle into *m* periods. Primary products are manufactured in every period. Remanufactured products, however, are added at the end of *commercial returns accumulation cycles*. In those periods, primary production rate is reduced by the amount of remanufactured products. As a result, it is assumed that the demand for each period is satisfied by either primary products or a mix of primary and remanufactured products. The targeted quality of parts used to manufacture primary products and the duration of time to accumulate commercial returns before they are remanufactured are the main variables in the model. After defining the problem and finding the product flow rates between facilities, an expression for the total profit has been derived. To address the complete impact of accumulation time for returned products the model includes consideration of time value of the money by using equivalent uniform costs for each period.

3.1 Problem definition

An expression is derived for the profit for a manufacturer who supplies the demand for a customer population utilizing a mix of primary and remanufactured products. This expression presents the total profit as a function of the targeted quality of parts used to manufacture primary products and the commercial returns accumulation cycle. The model is a closed-loop supply chain network flow model, shown in Fig. 1, with the notations defined in Table 1. The facilities in the closed-loop supply chain include factory, distribution center, retailer, customer, return center, and remanufacturing center. For simplicity of formulation, just one facility in each node has been considered. It should be noted that in this study, the problem is formulated in a dimensionless environment. It is assumed that

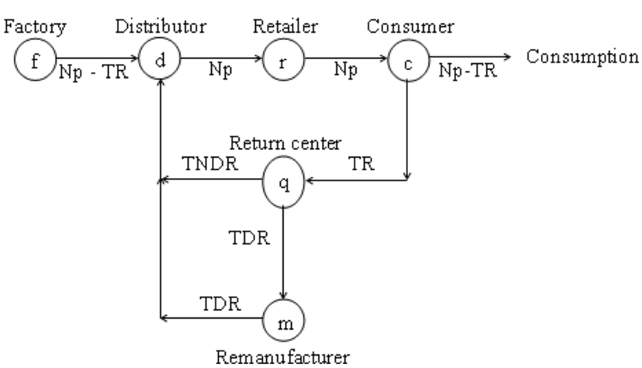

Fig. 1 Closed loop supply chain model

Table 1 Notation

Variable	Definition
D	Demand per cycle
TR	Total number of returns
TNDR	Total number of non-defective returns
TDR	Total number of defective return
PV	Present value of a cost or profit
EUC	Equivalent uniform cost
N_p	Total number of primary products manufactured in each cycle
N_{pS1}	Number of primary products manufactured in cycles 1 to m+1
N_{pS2}	Number of primary products manufactured in cycle m+2
N_{pS3}	Number of primary products manufactured in cycle m+3
i	Return percentage
m	Accumulation time (in terms of the number of cycles that every return center waits before dealing with the retuned products)
d	Percentage of returned products that are truly defective
S	Shipping cost function in terms of number of products being shipped
P	The cost of quality inspection per returned product in the return center
Q	The cost of repackaging per returned product in the return center
T	The cost of remanufacturing per returned product in the remanufacturing center
e	Interest rate per period
u	Discount for remanufactured products
CS	Cost function of producing one primary product in terms of parts defective rate
n	Total number of parts in each product
p_i	Parts defective rate

the price of a unit of primary product is unity and all other costs are stated in terms of fractions of the unit primary product cost.

3.2 Required primary production rate in each period to satisfy a fixed demand

Supplying demand is assumed to take place in one of the following fashions: (a) The demand is supplied by only primary products, (b) primary and repackaged false returns supply the demand, and (c) the demand is supplied by primary and remanufactured products. As a result, the primary production rate to supply a demand of D can be defines as follows:

- In periods where no returned product is processed, all demands are met by primary products with the production rate of N_{pS1}.
- In periods where returned products are processed to the point where false failure returns are sent back to the market (one period after accumulation time), the volume of primary product is reduced to N_{pS2}.

- In periods where defective units are remanufactured (two periods after accumulation time), the volume of primary products is lowered to N_{pS3}.
- When all accumulated returned products are processed and consumed in the market, the volume of primary products goes back to N_{pS1}.

We refer to the total length of periods that cover situations (a), (b), and (c) as a production cycle. It can be shown that if accumulation time is m periods and there is a need for one period for processing false returns and one more period to process remanufacturing defective products, the cycle c will consist of m periods. Production volumes for each of the above periods are calculated below:

Considering a return rate of i, in periods 1 to m+1, we have

$$\text{Number of products sold in each period}: N_p(1–i) = \text{demand in each period } D. \text{ Therefore, } N_{pS1} = D/(1–i),$$

where N_{pS1} is the number of manufactured primary products in periods 1 to m+1. The return center starts dealing with the returns at the beginning of m+1 period, repackages all the non-defective products and sends them to distribution center at the beginning of m+2 period.

In period m+2, all the non-defective returned products are sent to the market. As a result, the manufacturer requires producing fewer products in this period:

$$D = N_{pS2} * (1–i) + m * N_{pS1} * i * (1–d).$$

Therefore,

$$N_{pS2} = \left[D - m * N_{pS1} * i * (1–d)\right] \Big/ (1–i),$$

where N_{pS2} is the number of manufactured primary products in period m+2 and d is the percentage of returned products that are actually defective.

In period m+3, all the defective returned products will be back in the market, so the manufacturer requires producing fewer products in this period:

$$D = N_{pS3} * (1–i) + m * N_{pS1} * i * d. \text{ Therefore,}$$

$$N_{pS3} = \left[D - m * N_{pS1} * i * d\right] \Big/ (1–i)$$

where N_{pS3} is the number of manufactured primary products in period m+3.

In general, production volume for primary products during each period could be stated as follows:

N_{pS1} for cycles km+j: j=0, m−3; N_{pS2} for cycle (k+1)*m; N_{pS3} for cycle (k+1)*m+1 for cycle number k. This relationship holds for all cycles lengths except where m<2. Values of m=1 and m=2 represent special cases where primary, repackaged, and remanufactured products will all contribute to meeting the sales in every period. Those situations have not been considered here as they defeat the purpose of accumulation of returns for better remanufacturing efficiency.

Based on the above formula, the production rate for primary products could be estimated for any given values of targeted defective rates in production of primary products. A sample of these estimates is shown in Fig. 2 for various values of return

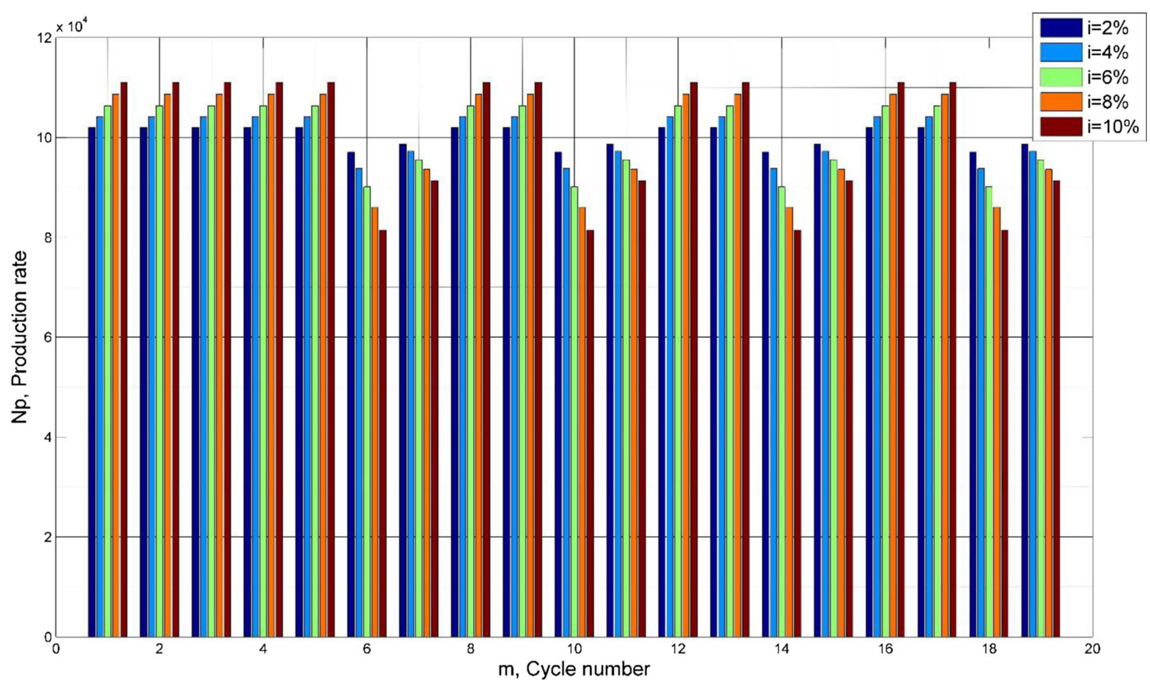

Fig. 2 Production rate based on a fixed demand=100,000, fixed m=4, and variable return percentages i

percentage, i=2, 4, 6, 8, and 10 %; a fixed demand, D=100,000; a fixed percentage of returned products that are actually defective, d=40 %; and a fixed m value, the number of periods that the return center will accumulate returned products.

For instance, as one could see in Fig. 2, where m=4, for the first five periods, N_p is slightly more than the demand and in 4+2=6th period, when all the non-defective returned products are added to the distribution stream, a drop is observed in the primary production rate. Therefore, the manufacturer can produce slightly fewer units and still be able to satisfy the demand. In the 4+3=7th period, all the defective returned products are remanufactured and sent back to the distribution center. As a result, the manufacturer can produce less units while still satisfying the demand. Similarly, the non-defective returned products collected in periods 5, 6, 7, and 8 will result in a reduction of N_p in the 10th period, and remanufacturing defective returned products collected in periods 5, 6, 7, and 8 will result in a reduction of N_p in the 11th period. If we disregard the first period, the rest of the graph for N_p is a repetition of the cycle consisting of periods 4, 5, 6, and 7. In calculating the total profit, the first m periods will be ignored and the steady-state situation will be investigated for remaining periods.

3.3 The product flow rate between facilities

In order to evaluate the time value of money and therefore the loss of value of returned products due to processing delays, we do our calculations for each period in a cycle separately and then find the equivalent uniform cost for one period. Assume the number of primary products manufactured in the factory in a period is N_p (in the previous part the required value of N_p to satisfy a fixed demand was calculated). These N_p products are distributed by the distribution center in the beginning of every period. Additionally, in some periods, the distribution center receives returned and remanufactured products to satisfy the demand with a combination of primary and remanufactured products.

The distribution center sends the products to the retailer. Therefore, in the beginning of every period, the retailer receives $D/(1-i)$ products. The transportation times between the distribution center and the retailer are ignored; hence, the retailer receives the products at the beginning of every period.

During each period, the retailer sells $D/(1-i)$ products and receives i percent commercial returns. Therefore, at the end of every period, the retailer has $i*D/(1-i)$ products that have been returned. This i, product return percentage, can vary from 5 to 9 % for hard goods and up to 35 % for high fashion apparel. Return percentages are also typically much higher for Internet and catalogue sales [1].

Some manufacturers require that retailers send every returned product back to return centers. For instance, HP and Bosch are highly brand-name conscious and have a policy that a product returned for any reason must be returned to their product return centers [15]. This policy has been adopted in this model, that is, the retailer sends all the returned products to the return center at the end of each period (or the beginning of the next period). Therefore, at the end of each period, the return center receives $i*D/(1-i)$ products from the retailer.

The return center waits a number of periods, m, to collect a reasonable amount of returned products to justify the start of the process of inspecting the quality of returned products, repackaging the false failure returns, and sending the defective products to the remanufacturing center. Hence, at the end of the mth period (or beginning of the m+1'th period), the return center starts dealing with $m*i*D/(1-i)$ returned products.

As mentioned earlier, not every returned product is actually defective. The percentage of truly defective returned products depends on the type of products, final quality of the products, and defective rate of each part in a product.

In this study, it is assumed that the percentage of truly defective products is d. Therefore out of $m*i*D/(1-i)$ returned products that the return center receives at the end of the mth period, only $d*m*i*D/(1-i)$ products are actually defective and should be sent to the remanufacturing center. The rest of the retuned products, $(1-d)*m*i*D/(1-i)$, should be repackaged, any missing part must be provided (since the consumers might neglect to put back all the parts such as an instruction manual or necessary items required for installation and so on), and should be sent back to the distribution center. This happens at the end of the m+1'th period, assuming the return center needs one period itself to deal with returned products. Therefore, at the end of m+1'th period, the distribution center receives $(1-d)*m*i*D/(1-i)$ products to be sent to the retailer to be sold as new.

Moreover, at the end of the m+1'th period, the remanufacturing center receives $d*m*i*D/(1-i)$ defective returns from the return center. We assume that it takes the remanufacturing center one period to remanufacture the defective products and send it to the market to be sold with a fixed discount. Therefore, at the end of m+2'th period, there are $d*m*i*D/(1-i)$ products in the market to be sold. A summary of all these product flows is presented in Table 2.

Table 2 Products flow between facilities

Description	No. of products
Total returns in every period	$i*D/(1-i)$
Total returns to the return center at the end of the mth period	$m*i*D/(1-i)$
Total non-defective returned products in the return center at the end of m+1'th period	$(1-d)*m*i*D/(1-i)$
Total non-defective returned products at the end of m+1'th period in the distribution center	$(1-d)*m*i*D/(1-i)$
Total defective returned products in the return center at the end of m+1'th period	$d*m*i*D/(1-i)$
Total defective products at the end of m+1'th period in the remanufacturing center	$d*m*i*D/(1-i)$
Total remanufactured products at the end of m+2'th period in the distribution center	$d*m*i*D/(1-i)$

3.4 Estimating the total profit

Here, the total profit that the manufacturer can make with selling the new and returned products is calculated. In this calculation, all the accompanied expenses such as shipping costs, quality inspection costs for returned products, repackaging costs for non-defective returned products, remanufacturing costs for defective products, and finally, the value in loss of money due to delays in processing of the returned products, are taken into account.

3.4.1 Total shipping costs considering the time value of money

We calculate the total shipping costs of the supply chain model for one cycle consisting of m periods and then find the equivalent uniform cost per period using the interest rate e for one period. All the shipping costs are assumed to be functions of the total number of products being shipped. Therefore, total cost for shipping N products would be $N*S(N)$, where $S(N)$, the shipping cost per item is a function in terms of N. Considering the price of a unit of primary product to be the unity, $S(N)$ could be any kind of declining function that depends on several variables such as the weight and size of products being shipped.

- Shipping costs of primary products from factory to distribution center:

  Based on Section 3.2, the manufacturer produces N_{pS1}, N_{pS2}, and N_{pS3} products in the first $m+1$ period, $m+2$ period, and $m+3$ period, respectively, and sends them to the distribution center. This cycle of production is repeated for periods $m+4$ to $2m+4$, $2m+5$, and $2m+6$, respectively, and so on. Using e as the interest rate per period, the present value of this cost can be calculated as follows:

$$\mathrm{PVS1} = N_{\mathrm{pS1}} * S(N_{\mathrm{pS1}}) * \left[\sum_{c=1}^{m-2} \frac{1}{(1+e)^{c}}\right] + N_{\mathrm{pS2}} * \frac{S(N_{\mathrm{pS2}})}{(1+e)^{m-1}} + N_{\mathrm{pS3}} * \frac{S(N_{\mathrm{pS3}})}{(1+e)^{m1}}$$

  Using the equivalent uniform cost (EUC) method, the total cost per period can be estimated as

$$\mathrm{EUCS1} = \mathrm{PVS1} * \frac{e(1+e)^{m}}{(1+e)^{m}-1}$$

- Shipping costs of combination of primary and remanufactured products from the distribution center to the retailer:

  The retailer will receive $D/(1-i)$ products in every period. Therefore, the equivalent uniform cost per period is

$$\mathrm{EUCS2} = D/(1–i) * S(D/(1–i))$$

- Shipping costs of commercial returns from the retailer to the return center:

  At the end of each period the retailer returns $i*D/(1-i)$ products to the return center. Therefore, the equivalent uniform cost per period is

$$\mathrm{EUCS3} = i * D/(1–i) * S(i * D/(1–i))$$

- Shipping costs of non-defective commercial returns from the return center to the distribution center:

  At the end of the $m+1$'th period—the first period under investigation—the return center sends returned products which are non-defective to the distribution center. The total number of non-defective products that the return center receives at the end of the m'th period is $(1-d)*m*i*D/(1-i)$. Therefore, the total shipping costs will be equal to $((1-d)*m*i*D/(1-i))*S((1-d)*m*i*D/(1-i))$. Therefore, the equivalent uniform cost per period is

$$\mathrm{EUCS4} = \left((1–d) * m * i * D\Big/(1–i)\right) * S\left((1–d) * m * i * D\Big/(1–i)\right) * \left(\sum_{i=0}^{m}(1+e)^{i}\right)^{-1}$$

- Shipping costs of defective commercial returns from the return center to the remanufacturing center:

  At the end of the $m+1$ period—the first period of the cycle under investigation—the return center sends all the defective products to the remanufacturing center. A total number of $d*m*i*D/(1-i)$ products is sent from the return center to the remanufacturing center. Therefore, the total shipping costs will be equal to $d*m*i*D/(1-i)*S(d*m*i*D/(1-i))$. Therefore, the equivalent uniform cost per period is

$$\mathrm{EUCS5} = d * m * i * D\Big/(1–i) * S\left(d * m * i * D\Big/(1–i)\right) * \left(\sum_{i=0}^{m}(1+e)^{i}\right)^{-1}$$

- Shipping costs of defective commercial returns from the remanufacturing center to the distribution center:

  At the end of the $m+2$ period—the second period of the cycle under investigation—the remanufacturing center sends all the remanufactured products to the distribution center. A total number of $d*m*i*D/(1-i)$ products is sent from remanufacturing center to the distribution center.

Therefore, the total shipping costs will be equal to $d*m*i*D/(1-i)*S(d*m*i*D/(1-i))$. This cost per period is

$$\mathrm{PVS6} = \frac{d*m*i*\frac{D}{1-i}*S\left(d*m*i*\frac{D}{1-i}\right)}{1+e}$$

Therefore, the equivalent uniform cost per period can be written as

$$\mathrm{EUCS6} = \mathrm{PVS6}*\left(\sum_{i=0}^{m}(1+e)^{i}\right)^{-1}$$

Adding all these costs:

$$\text{Total equivalent uniform shipping cost per period} = \Pi_{S}$$
$$= \mathrm{EUCS1} + \mathrm{EUCS2} + \mathrm{EUCS3} + \mathrm{EUCS4} + \mathrm{EUCS5} + \mathrm{EUCS6}$$

3.4.2 Total quality inspection, remanufacturing, and repackaging costs

At the end of the mth period, the return center receives a total of $m*i*D/(1-i)$ returns. The return center has to pay for labor, quality inspections, and repackaging costs. It is assumed that for every returned product, the return center spends P dollars for the quality inspection. This cost consists of the cost of inspecting for defects and deciding whether the product should be repackaged and sent to the market again or be sent to remanufacturing center. There is also a cost for repackaging and providing any missing part for the products that is sent to the retailer. It is assumed this cost is Q dollars per returned product. Finally, the remanufacturing center has to spend T dollars to remanufacture failed products. Note that all these values are functions of the number of products (similar to shipping cost function).

$$\begin{aligned}&\text{The total present value of quality inspections, repackaging}\\&\text{and remanufacturing costs} = \mathrm{PVR1} = m*i*D/(1-i)\\&\quad *P(m*i*D/(1-i))\\&\quad + (1-d)*m*i*D\sqrt{a^2+b^2}\Big/(1-i)\\&\quad *Q\Big((1-d)*m*i*D\Big/(1-i)\Big)\\&\quad + d*m*i*D\Big/(1-i)\\&\quad *T\Big(d*m*i*D\Big/(1-i)\Big)\Big/(1+e)\end{aligned}$$

where P, Q, and T represent the costs of quality inspection, repackaging, and remanufacturing of products, respectively. Similar to the shipping cost function, these are decaying functions in terms of the number of products being handled. In a steady-state situation, when a cycle consists of m periods, quality and repackaging costs happen at period $m-2$ and remanufacturing at period $m-1$. Then the present worth at the beginning of the cycle will require the above value to be brought back to the beginning of the cycle. That is why it has to been multiplied by $1/(1+e)^{m-2}$. Then, the result has to be multiplied by $\frac{e(1+e)^m}{(1+e)^m-1}$ to obtain the uniform equivalent cost for each period.

3.4.3 Total profit

As described earlier in Section 3.2, the manufacturer produces N_{pS1} primary products in periods 1 to $m-2$ and N_{pS2} and N_{pS3} products in the $m-1$ and the m periods of each cycle, respectively. We assumed that the price for one primary product is unity, therefore, the company is to receive a total revenue of $1*(1-i)*N_{\mathrm{pS1}}$, $1*(1-i)*N_{\mathrm{pS2}}$, and $1*(1-i)*N_{\mathrm{pS3}}$ in the corresponding periods of each cycle. The present value of the total profit of selling the primary products can be calculated as follows:

$$\mathrm{PVP1} = (1-i)*N_{\mathrm{pS1}}*\left[\frac{(1+e)^{m-2}-1}{e(1+e)^{m-2}}\right] + (1-i)*N_{\mathrm{pS2}}*\frac{1}{(1+e)^{m-1}} + N_{\mathrm{pS3}}*\frac{1}{(1+e)^{m}}$$

Therefore, the equivalent uniform profit per cycle can be written as

$$\Omega_{R1} = \mathrm{EUCP1} = \mathrm{PVP1}*\frac{e(1+e)^m}{(1+e)^m-1}$$

Moreover, at the end of the mth period, the company will get back $(1-d)*m*i*D/(1-i)$ non-defective products. At the end of the $m+1$'th period, the return center will send these products back to the retailer and the retailer sells them as new for the same unit price (we assume the company is legally able to sell these products as new). However, if the decline in value of the returned products is e%, in each period, the company will lose $1/(1+e)$ of the product's value. For the ease of calculations, we assume this value is the same as the interest rate.

Considering the time value of money and the fact that the more time a product waits to be remanufactured, the more value it loses, the profit of the company from selling all the non-defective returned products would be

Profit from selling the non-defective returned products

$$= \Omega_{ndR} = \sum_{n=1}^{m} \frac{(1-d)*i*D/(1-i)}{(1+e)^{n+1}}$$

Moreover, the profit of the company from selling all the defective returned products considering a discount of $u\%$ would be

Profit from selling defective returned products $= \Omega_{dR}$

$$= \sum_{n=1}^{m} \frac{(1-u)d*i*D\Big/(1-i)}{(1+e)^{n+2}}$$

All the non-defective returned and defective products will be sold in the $m-1$ and m periods of each cycle. Therefore, the present value of the total profit of selling the returned products can be calculated as follows:

$$\mathrm{PVP2} = \frac{(1-d)*i*D/(1-i)}{(1+e)^{m-1}} + \frac{(1-u)d*i*D/(1-i)}{(1+e)^{m}}$$

Therefore, the equivalent uniform profit per period can be written as

$$\Omega_{R2} = \mathrm{EUCP2} = \mathrm{PVP2} * \frac{e(1+e)^m}{(1+e)^m - 1}$$

In calculating the profit in above equation, it has been assumed that all the returned products are sold in the same period that they have been sent back to the retailer.

3.4.4 Manufacturing cost of producing primary products

Although it is clear that the cost per part is a decreasing or at least nonincreasing function of the parts' quality, the actual form of this function varies depending on production and design conditions. Here, it is assumed that p is the probability of a part used in the primary product is defective. Therefore, the production cost of primary product is CS(p), a declining function of p. Therefore, the cost of primary product production will be N_{pS1}*CS(p), N_{pS2}*CS(p), and N_{pS3}*CS(p) in the corresponding periods of a cycle. Therefore, the present value of the manufacturing cost of primary products is equal to

$$\mathrm{PVM1} = N_{pS1} * \mathrm{CS}(p) * \frac{(1+e)^{m-2} - 1}{e(1+e)^{m-2}} + N_{PS2} * CS(p) * \frac{1}{(1+e)^{m-1}} + N_{PS3} * \mathrm{CS}(p) * \frac{1}{(1+e)^{m}}$$

Therefore, the equivalent uniform cost per period can be written as

$$\Pi_M = \mathrm{EUCM1} = \mathrm{PVM1} * \frac{e(1+e)^m}{(1+e)^m - 1}$$

With above calculation the total profit of the company in one period will be equal to

$$\text{Total profit} = \Omega_T = \Omega_{R1} + \Omega_{R2} - \Pi_M - \Pi_R - \Pi_S$$

4 Numerical examples

In order to demonstrate the application of the proposed method, several numerical examples are presented here. In all examples, it is assumed that the price of one unit of primary product is unity, 1. The details of these examples are presented below.

As mentioned earlier, the shipping, quality inspection, repackaging, and remanufacturing costs are all functions of batch size or the number of products being handled. A decreasing function could be picked for this part based on the type of product and other corresponding factors. Here, we assume a decreasing power function for all abovementioned costs.

Table 3 shows the values considered for all the parameters used in this example. Here, the variation of the total profit is observed as a function of the quality of individual parts used in the product. This function is then maximized to obtain the optimum target quality of primary products. It is assumed that every defective product would be returned to the retailer. Therefore, the total number of defective returns in one period, N_p*i*d, is equal to the total number of products with at least one defective part.

If each product consists of n parts and the probability of a part being defective is assumed to be the same for all parts and equal to p, the expected number of defective products will be $N_p*m*[1-(1-p)^{nc}]$. Therefore, the return rate of products is $i=[1-(1-p)^{nc}/d]$.

Figure 3 shows the total profit function (based on the equivalent uniform costs and profits per period) that the company can earn as a function of quality of parts used to manufacture primary products and the number of periods that the company will hold the returned products before remanufacturing or repacking. It can be seen that manufacturing parts with low defective rates, 0.002 to 0.003, will result in a substantial decrease in total profit. Moreover, manufacturing parts with high defective rates, such as 0.007 and 0.008, will also result in a decrease in profit.

In order to find the optimum values for m and p, the contour display has been plotted for the same example in Fig. 4. It can be seen that the optimum values for m are 5 and 6 and the optimum values for p are between 0.004 and 0.005. A value of

Table 3 Values used for numerical example

Parameters	Description	Value
N_p	Total products produced in every period	Variable (function of i)
D	Demand in each period	500,000
i	Return rate	Variable (function of p)
m	Number of periods	$1<m<12$
nc	Number of parts in a product	10
e	Decay of value of products and interest rate	2.5 % per period
d	Defective rate of returned products	40 %
p	Quality or percentage of defective rate of parts	$0.002<p<0.008$
C	Cost function based on defective rate pi	$0.354*p^{-0.092}$
Ω_T	Total profit for one period	Outcome
$S(N)$	Shipping cost function	$0.468*N^{-0.240}$
$P(N)$	The cost of quality inspection function	$0.716*N^{-0.207}$
$Q(N)$	The cost of repackaging function	$0.488*N^{-0.307}$
$T(N)$	The cost of remanufacturing function	$5.054*N^{-0.112}$
u	Discount for remanufactured products	30 %

0.004 for p, in a product consisting of 10 parts, will result in production of 4.9 % defective products.

If the manufacturer produces products with target defective rate of 0.005 but instead of choosing the optimum value of m (5 or 6 in this example), starts remanufacturing after every period ($m=1$), the company will lose a total profit of profit($pi=0.005$, $m=5$)−profit($pi=0.005$, $m=1$)=225,122−213,743=11,379 in each period. If we assume the unit price of $200 for each primary product, the total loss would be equal to $275,800 in each period. If a period is 1 month, the company will face a total loss of $14,390,554 on a yearly basis. This huge loss in profit should encourage managers to

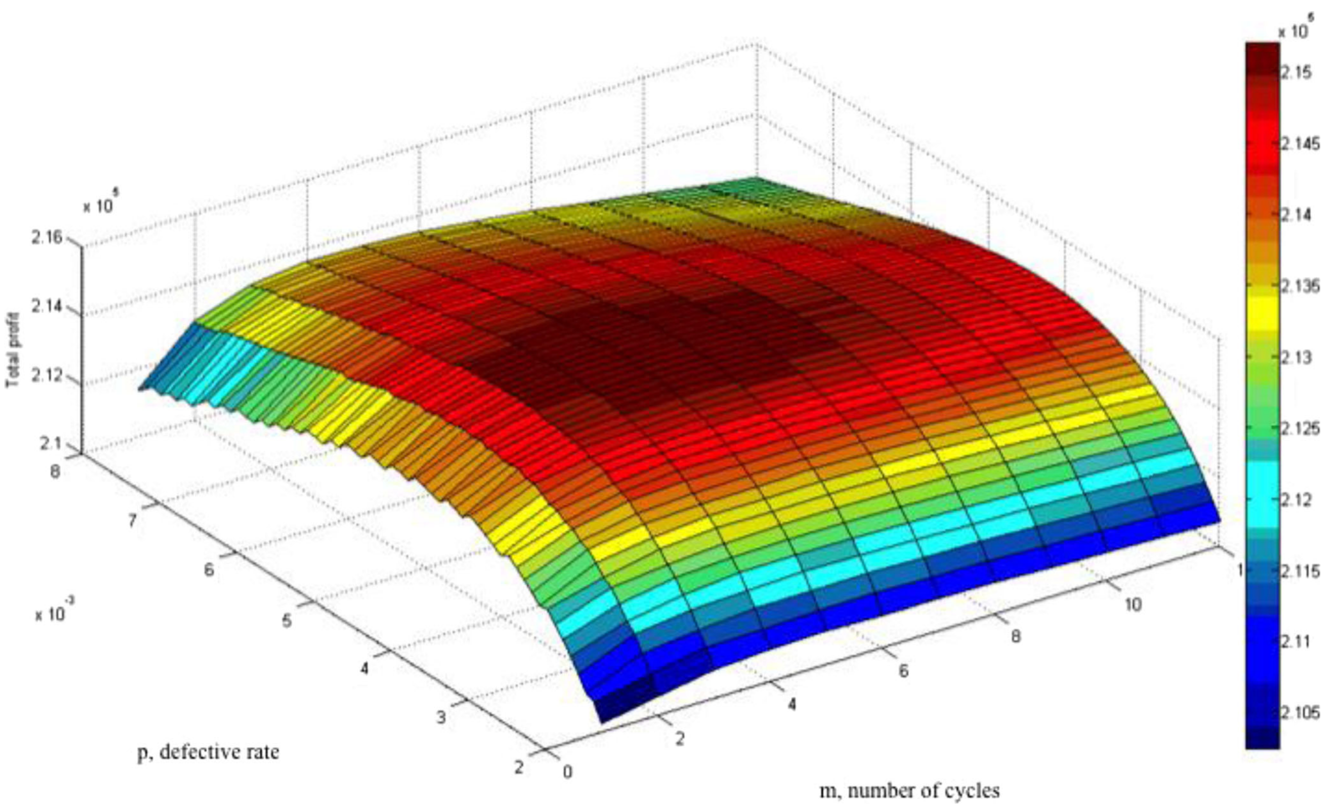

Fig. 3 Total profit function for $D=500{,}000$

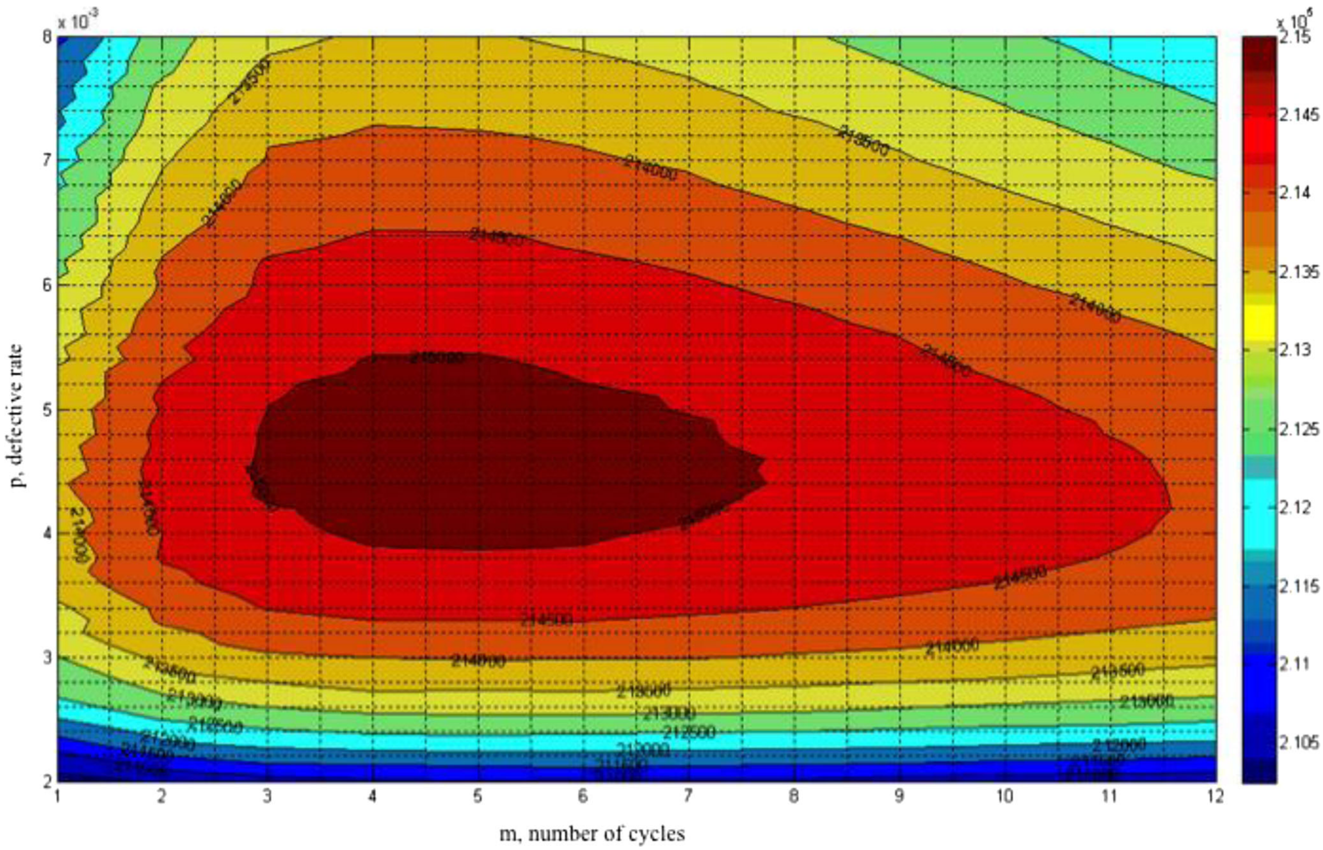

Fig. 4 Contour display of total profit function

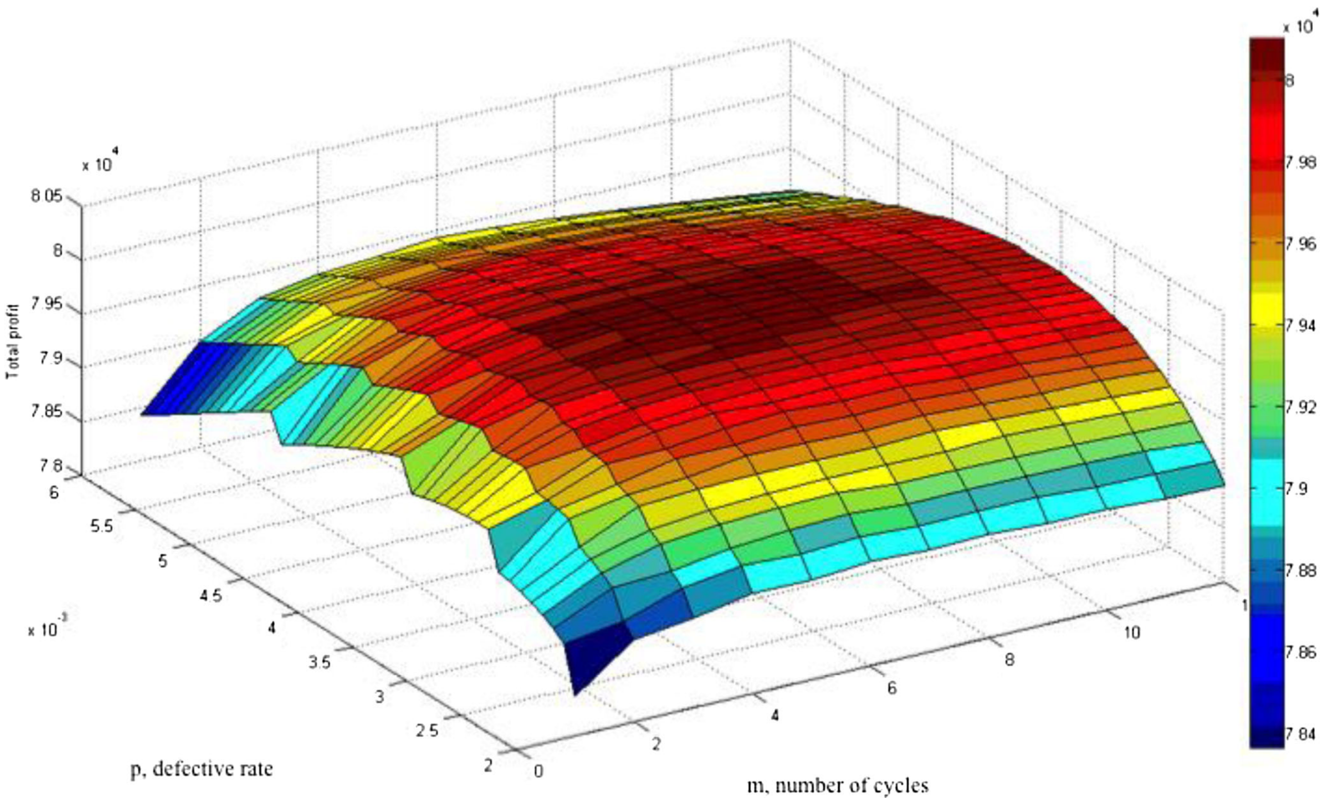

Fig. 5 Total profit function for D=200,000

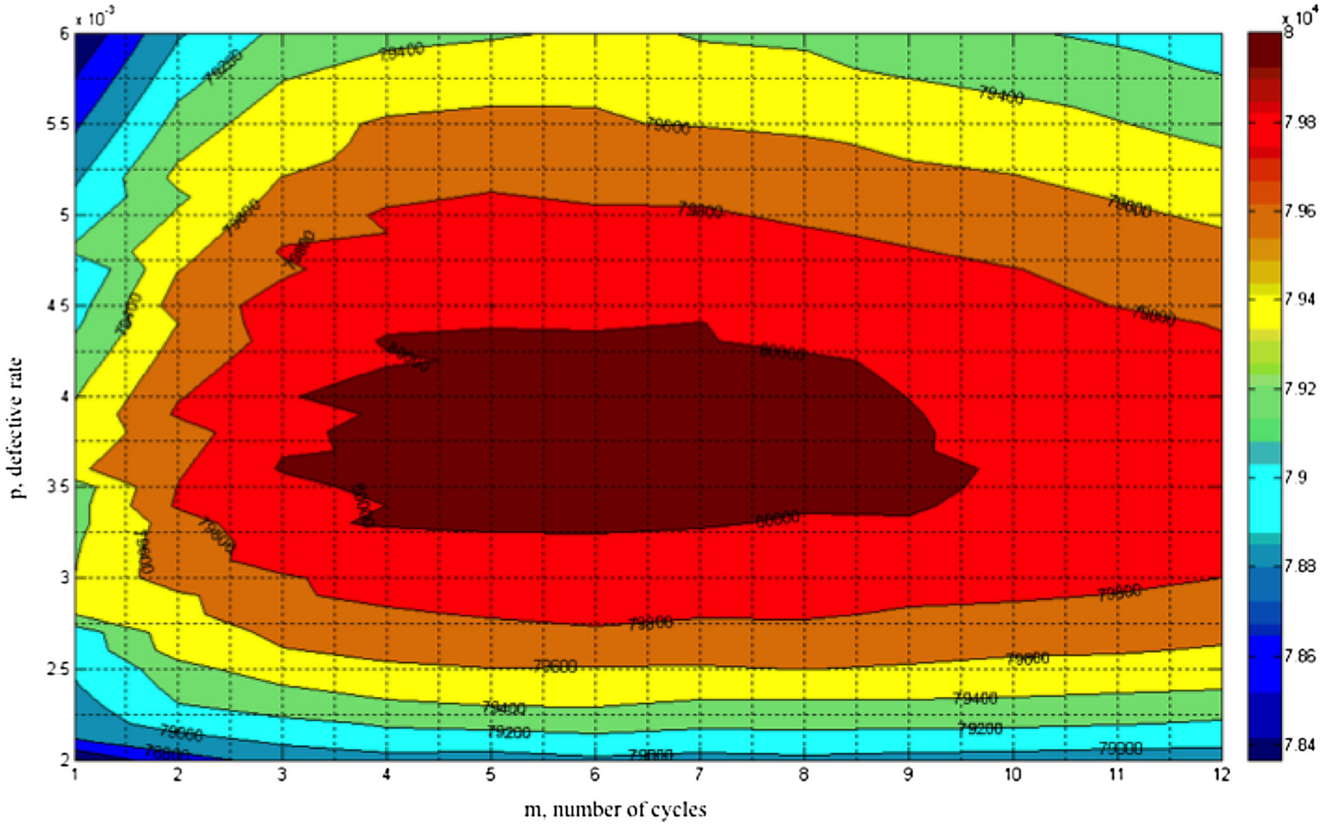

Fig. 6 Contour display of total profit function D=200,000

find the optimum value of m and pi, for their manufacturing operations.

On the other hand, waiting too long for remanufacturing the returned products will cause a substantial loss in the value of the returned products and therefore a loss in profit. For example, if the manufacturer produces products consisting of parts with a target defective rate of 0.005 but instead of choosing the optimum value of m starts remanufacturing the returned products after the eleventh period (m=11), the company will lose a total profit of profit(p=0.005, m=6)−profit(p=0.005, m=11)=215,122−214,433=689 in each period. Assuming the unit price of $200 for each primary product, the total loss would be equal to $137,800 in each period. If a period is 1 month, the company will face a total loss of $7,190,059 in a yearly basis.

Clearly, the change in demand will result in different values of optimum p and m. Figures 5 and 6 are for a demand of 200,000. A decrease in the optimal p value and an increase in the range of optimal m could be perceived. Moreover, Table 4 shows the absolute optimum value of ms and ps for different values of demand. This most profitable pair of (m, pi) has been calculated by finding the profit for each point of the graphs shown in Fig. 4 and then finding the maximum profit.

Also from Table 4, it can be seen that in almost every case, an increase in demand will allow the manufacturer to produce the parts with more defective rate. Although this will result in an increase in return rates, dealing with a large amount of products in each period will reduce costs for shipping, quality inspection, repackaging, and remanufacturing. A more detailed plot of relationship between the maximum p and the demand is presented in Fig. 7. As shown in the figure, a power function has been used to estimate the relationship between demand and the optimum value of p. This relationship is a function of multiple factors, conditions, and values that have been assumed in this example as stated in Table 3. However, it can still be used as a

Table 4 Optimal values of pi and m for different demands

Demand	m	pi
600,000	5	0.0046
500,000	5	0.0046
400,000	5	0.0042
300,000	6	0.0043
200,000	6	0.0038
100,000	6	0.0033
50,000	7	0.0029
40,000	8	0.0028
30,000	9	0.0025

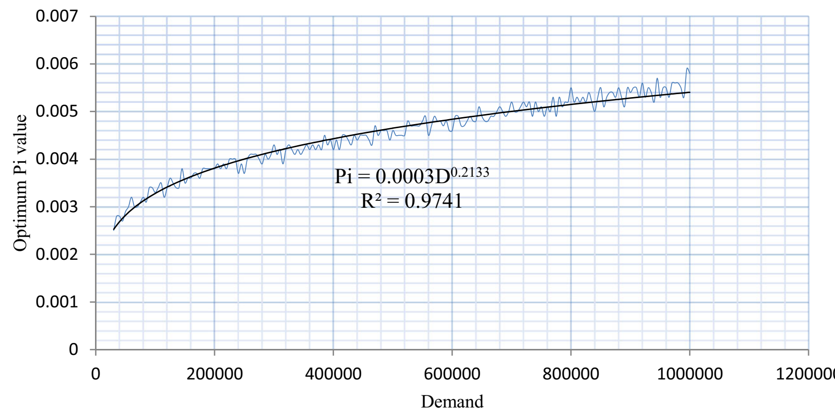

Fig. 7 The relationship between optimum *pi* value and demand

guideline for managers to find the optimum value of *p* based on the demand in each period.

5 Conclusion

This study investigated a production environment in which manufacturers have a policy of providing replacements for returned products and recycling the returned products, whether by just repackaging them and sending them back to the market or by remanufacturing them in the remanufacturing center. The accumulation time before starting the remanufacturing process has been considered as a decision variable. A model was developed which uses the targeted quality of parts used to manufacture primary products and the waiting time before starting the remanufacturing process as decision variables in a profit function. This model was then optimized to provide the desired quality to target and the optimum amount of time to accumulate returned products before starting the remanufacturing process.

The results indicated many advantages for using this system of production and recycling. Most importantly, it showed that even in environmentally conscious manufacturing circumstances, the design for the highest possible quality does not necessarily result in the best operation policy. Lower design quality targets could be used to maximize profit without sacrificing environmental concerns.

Moreover, focusing on the time value of money for returned products resulted in finding the total loss due to delays in remanufacturing process. Based on calculations for a numerical example, it was found that for a fixed demand and parts defective rate, a company will face a total loss of $7,190,059 in a yearly basis if they do not optimize their operation and recycling policies. If remanufacturing is introduced and related policies are optimized, this study shows commercial product returns can yield a substantial profit for the company.

An immediate extension of the work presented here is to modify the model in order to include cases in which some returned products have to be disposed since there is no justification for remanufacturing them. Furthermore, it can be assumed that the remanufactured parts and products that have been repackaged has a less chance of getting returned since they have been checked for a defect two times and there is probably a good chance that they are free from defects.

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