# AVERAGE COSTS VERSUS NET PRESENT VALUE: A COMPARISON FOR MULTI-SOURCE INVENTORY MODELS

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# Average Costs versus Net Present Value: a comparison for multi-source inventory models

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**Abstract**

While the net present value (NPV) approach is widely accepted as the right framework for studying production and inventory control systems, average cost (AC) models are more widely used. For the well known EOQ model it can be verified that (under certain conditions) the AC approach gives near optimal results, but does this also hold for more complex systems? In this paper it is argued that for more complex systems, like multi-source systems, one has to be extremely careful in applying the AC approach on intuition alone, even when these systems are deterministic. Special attention is given to a two-source inventory system with manufacturing, remanufacturing, and disposal, and it is shown that for this type of models there is a considerable gap between the AC approach and the NPV aprroach.

**Keywords:** Net present value, average costs, inventory control, manufacturing, remanufacturing, disposal, holding costs.

## 1 Introduction

Several authors (e.g. Hadley, 1964; Trippi, 1974; Thompson, 1975; Hofmann, 1998; Klein Haneveld and Teunter, 1998) have argued that *for the EOQ model* the average cost (AC) framework as an approximation to the superior net present value (NPV) framework leads to near optimal results under the following conditions:

- Products are not moving too slow,
- Interest rates are not too high,
- The customer payment structure does not depend on the inventory policy.

The first two conditions have to guarantee that compounded interest does not effect the results too much. That the latter condition is crucial was first put forward by Beranek (1966), who's concern was confirmed later by Grubbström (1980) and Kim *et al.* (1984).

The main objections against the average cost approach, as it is usually applied as an approximation to the net present value approach, are threefold:

**O1** The time value of money is not explicitly taken into account,

**O2** There is no distinction between out-of-pocket holding costs and opportunity costs due to inventory investment, while other sources of opportunity costs/yields (fixed ordering costs, product sales) are not taken into account at all.

**O3** Initial conditions are not taken into account

Yet, the net present value approach is often rather complicated, so an approximation may still be preferred.

Several authors have tried to deal with the above problems by showing that a certain transformation of the holding cost parameters in EOQ-type models gives near optimal results from an NPV perspective. This, however, shifts the problem to finding the right transformation. Up to now only ad hoc solutions have been given that are often very counter-intuitive (see e.g. Beranek, 1966; Corbey *et al.*, 1999). No general principle has been developed to solve the transformation problem.

This paper intends to systematically analyze the differences between the AC and NPV approach and its consequences for modeling inventory systems. To that end we will analyze a number of deterministic models with increasing complexity, starting with the standard EOQ model and moving towards multi-echelon and multi-source models. It is shown that there are basically two classes of systems: 1. systems for which a transformation of model parameters exists that is independent of decision variables, such that the AC approach and the NPV approach are approximately equal, and 2. systems for which such a transformation does not exist.

This paper is further organized as follows: In the next section we propose a general principle that allows us to handle the NPV approach for deterministic systems in a very simple way. Moreover, with this principle we can easily compare the AC approach with the NPV approach. We then show how the NPV approach compares to the AC approach for the EOQ model (Section 3), multi-echelon systems (Section 4), and multi-source systems (Section 5). The theoretical results are further illustrated by a small numerical study in Section 6. We end with a summary and discussion of the main results in Section 7.

## 2 A general principle for the NPV approach in deterministic models

We define the *Net Present Value* ($NPV$) as the total discounted cash-flow over an infinite horizon. Additional to the $NPV$ we define the *Annuity Stream* ($AS$) as

$$AS = r\{NPV\}.$$

where $r$ denotes the discount rate. The annuity stream is the transformation of a set of discrete and/or continuous cash flows to one continuous stream of cash-flows, such that the latter has the same net present value as the original set of cash-flows. The notion of an annuity stream is useful, since it can be directly compared with average costs.

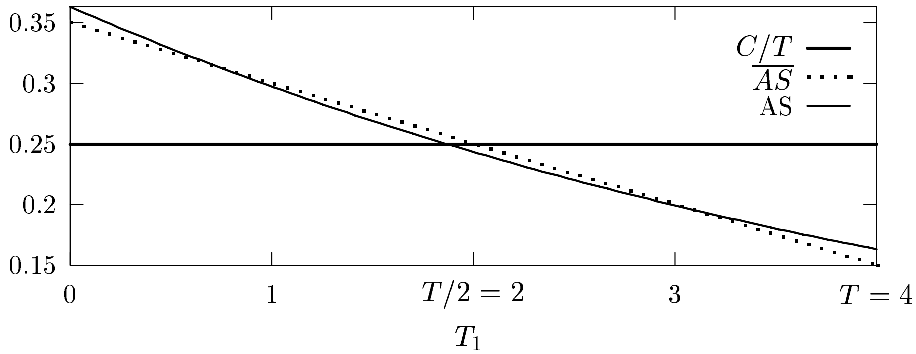


**Figure 2.1** Comparison between the average cash-flow per time unit ($C/T$), the anuity stream ($\overline{AS}$), and its linearisation ($AS$) for $T = 4$, $C = 1$, and $r = 0.2$.

If $T$ denotes the cycling time of a discrete cash-flow $C$, with first occurrence time $T_1$, then the annuity stream is given by

$$AS = rC \sum_{n=0}^{\infty} \mathrm{e}^{-r(T_1+nT)} = \frac{rC\mathrm{e}^{-rT_1}}{1-\mathrm{e}^{-rT}}, \tag{1}$$

This can be written as the McLaurin expansion in $r$

$$AS = \frac{rC\mathrm{e}^{-rT_1}}{1-\mathrm{e}^{-rT}} = \frac{C}{T} + C\left[r\left(\frac{1}{2} - \frac{T_1}{T}\right) + O(r^2 \max\{T, T_1\})\right],$$

so that we have the following linearisation in $r$ of the annuity stream:

$$\overline{AS} = \frac{C}{T} + rC\left(\frac{1}{2} - \frac{T_1}{T}\right). \tag{2}$$

Note that in most practical applications $r$ is small and $0 \leq T_1 \leq T$, so that the above approximation is quite reasonable.

The first term of (2), $C/T$, denotes the average cash-flow per time unit, as it would follow from a standard AC calculation. The second term may be viewed as a first order correction term to account for the time value of money. This is graphically shown in Figure 2.1. Approximately, the AC approach underestimates the interest component of the annuity stream if $T_1 \leq T/2$ and overestimates otherwise. The results of both approaches are the same if $T_1 \approx T/2$.

The above only holds for discrete cash-flows, but we can do a similar analysis for continuous cash-flows. Suppose a continuous cash-flow $p$ with rate $\lambda$ that starts at time $T_1$, then the annuity stream is given by

$$\begin{aligned} AS &= rp\lambda \textstyle\int_{T_1}^{\infty} \mathrm{e}^{-rt}\mathrm{d}t \\ &= rp\lambda\mathrm{e}^{-rT_1} \\ &= p\lambda[1 - rT_1 + O(r^2 {T_1}^2)] \end{aligned}$$

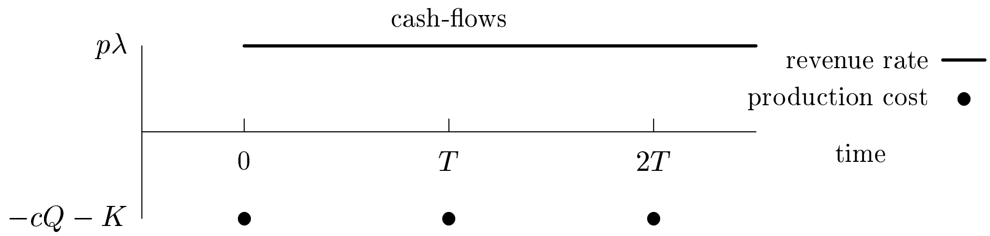


**Figure 3.1** Relevant cash-flows for the EOQ model with continuous demand.

$$\approx \quad p\lambda[1 - rT_1]. \tag{3}$$

The way that the AC approach usually deals with the *underestimation* of the interest component for cash-flows related to variable production costs is to add a certain factor to the out-of-pocket holding cost parameter. This factor is usually taken as the interest rate $r$ times the 'value' of the stocked item. This approach has a number of disadvantages. First, it assumes that the overestimation is proportional with average inventory. We will show that this does not need to be the case. In fact, size and timing of cash-flows are dependent on *cycle times* rather than the existence of physical stocks. Second, it only deals with *under*estimation of the interest component and not with *over*estimation, since the value of a stocked item is usually taken to be positive. Third, this approach only considers the interest components of variable production costs, while interest components of all other cash flows (fixed costs, sales, etc.) are not taken into account. Finally, it is unclear what is meant by the 'value' of a stocked item, since this depends on the type of decision that has to be made.[1]

# 3 From NPV to AC with the EOQ model

First consider the basic EOQ model in an NPV framework (Figure 3.1). Demand for a product with selling price $p$ is continuous with rate $\lambda$, generating a continuous cash inflow of $\lambda p$ per time unit. Every $T$ periods a batch of $Q$ products is produced against variable cost $c$ per product and fixed cost $K$ per batch (zero lead time) starting at time $t = 0$. To keep the analysis simple and transparent we will not consider out-of-pocket holding costs. Note that in the AC framework holding costs appear as an approximation to the annuity stream to account for interest components. We will refer to this holding cost parameter as the 'opportunity cost rate of inventory investment'.

The total annuity stream for this deterministic system consists of the annuity stream due to *a)*

[1] Depending on the type of decision that has to be made one could say that a product return has value zero if it has been obtained for free. At the same time one could say it has value $c_p - c_r$, since after remanufacturing against cost $c_r$ it can be sold for $c_p$. As a third option one could say that its value is $c_m - c_r$, since this is the difference between manufacturing against cost $c_m$ and remanufacturing against cost $c_r$.

the variable revenues and production costs ($AS_v$)

$$\begin{aligned} AS_v &= r\left(p\lambda\int_0^\infty \mathrm{e}^{-rt}\mathrm{d}t - cQ\sum_{n=0}^{\infty}\mathrm{e}^{-rnT}\right) \\ &= p\lambda - \frac{rcQ}{1-\mathrm{e}^{-rT}} \\ &\approx (p-c)\lambda - rcQ/2, \end{aligned} \tag{4}$$

and *b)* the annuity stream due to fixed set-up costs ($AS_f$)

$$\begin{aligned} AS_f &= -r\textstyle\sum_{n=0}^{\infty} K\mathrm{e}^{-rnT} \\ &= -\tfrac{rK}{1-\mathrm{e}^{-rT}} \\ &\approx -K\lambda/Q - rK/2, \end{aligned} \tag{5}$$

where we have used linearizations (2) and (3) with $T_1 = 0$. Combining (4)–(5) we arrive at the approximated total annuity stream function

$$\overline{AS} = (p-c)\lambda - K\lambda/Q - rcQ/2 - rK/2 \tag{6}$$

The first term in (6) denotes marginal net profits per time unit, and the second term denotes the average set-up costs per time unit. The other terms are interest components.

The standard AC approach calculates the average profit ($AP$) function as

$$AP = (p-c)\lambda - hQ/2 - K\lambda/Q, \tag{7}$$

where $h$ is the holding cost rate to account for the opportunity costs of inventory investment. Optimizing (7) leads to the well-known EOQ formula, but it is not immediately clear what the value of $h$ should be. However, if we want that optimizing $AP$ gives the same order size as optimizing $\overline{AS}$ we should choose $h = rc$. Although this value will appeal to most people's intuition it is important to note that more complicated models, as the ones encountered in the remainder of the paper, call for more complicated holding cost rates for which an intuitive explanation is often hard to give.

## 4 Multi-echelon systems

Consider a two-echelon system consisting of processes $i$, $i \in \{1,2\}$, with lead time $L_i$, and processing cost $c_i$ (Figure 4.1). Here, $S$ is a stocking point for serviceable inventory. A production batch of size $Q$ is initiated every $T$ time units starting at time $T_1 = 0$. As soon as process 1 finishes process 2 starts. As soon as process 2 finishes, the batch enters serviceable inventory (Figure 4.2). Note that production costs are incurred at the beginning of each process and that product sales only start after the first production batch has entered the serviceable inventory, i.e., at time $L_1 + L_2$.

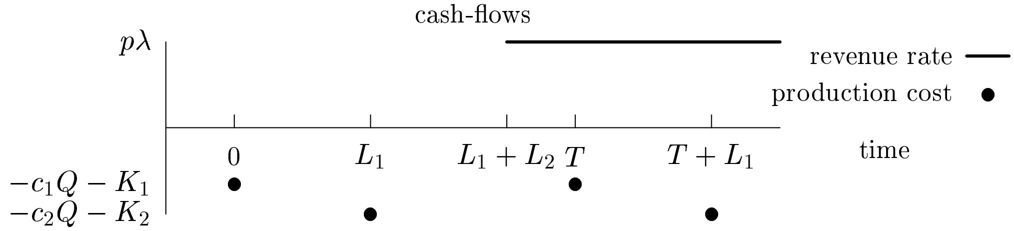


**Figure 4.1** Relevant cash-flows for the two-echelon system.

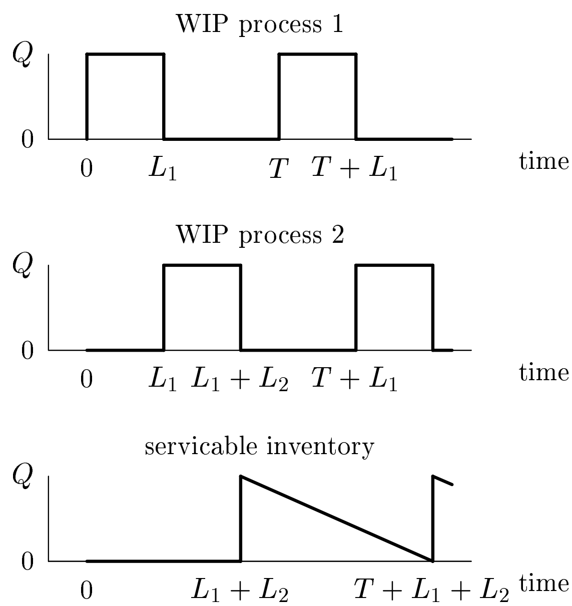


**Figure 4.2** The inventory processes of a two-echelon system.

A formal deduction of $AS_v$ gives

$$
\begin{aligned}
AS_v &= r\left(\frac{p\lambda \mathrm{e}^{-r(L_1+L_2)}}{r} - \frac{Qc_1 + Qc_2\mathrm{e}^{-rL_1}}{1-\mathrm{e}^{-rT}}\right) \\
&\approx (p - c_1 - c_2)\lambda - r\left((c_1+c_2)Q/2 - c_2L_1\lambda\right) - rp(L_1+L_2)\lambda. \qquad (8)
\end{aligned}
$$

The first term in (8) is just the marginal net profits per time unit, whereas the second term denotes the opportunity costs of inventory investment. The last term represents the opportunity costs of delayed product sales.

The traditional average cost approach would calculate the average profit function as the average net marginal profits per time unit minus the average holding costs per time unit,

$$AP_v = (p - c_1 - c_2)\lambda - h_1L_1\lambda - h_2L_2\lambda - h_sQ/2, \qquad (9)$$

where the second term is the average work in process inventory of process 1 charged with opportunity holding cost rate $h_1$, the third term is the average work in process inventory of process 2, charged with rate $h_2$, and the fourth term is the average serviceable inventory charged with rate $h_s$. Equation (9) corresponds to (8) if we employ the following transformation of cost parameters:

$$
\begin{aligned}
h_1 &\rightarrow r(p - c_2) \\
h_2 &\rightarrow rp \\
h_s &\rightarrow r(c_1 + c_2)
\end{aligned}
$$

The parameter $h_s$ can be interpreted intuitively as the interest rate times the total marginal production costs. The other holding cost rates are less intuitive, but that is not really a problem since for any value of these parameters the difference between NPV and AC will merely be a constant.

The annuity stream due to fixed set-up costs is

$$
\begin{aligned}
AS_f &= -r\left(\frac{K_1 + K_2\mathrm{e}^{-rL_1}}{1-\mathrm{e}^{-rT}}\right) \\
&\approx -\frac{(K_1+K_2)\lambda}{Q} - r\left(\frac{K_1+K_2}{2} - \frac{K_2L_1\lambda}{Q}\right).
\end{aligned}
$$

In the traditional average cost approach opportunity costs of set-ups are never explicitly taken into account (compare to the EOQ model, where opportunity costs of set-ups are a constant and can be left out). Here, however, we see that the opportunity costs do depend on the order size $Q$ and can no longer be discarded. Again, we can map (up to a constant) the average cost approach to the linearization of the annuity stream by the transformation

$$
\begin{aligned}
K_1 &\rightarrow K_1 \\
K_2 &\rightarrow K_2(1 - rL_1)
\end{aligned}
$$

**Figure 5.1** Schematic representation of a manufacturing/remanufacturing system.

Summarizing, we can say that the traditional average cost approach is still applicable for multi-echelon structures, as long as the right transformations of model parameters are used. This however results in a paradoxical situation: Using the average cost approach in order to avoid an NPV analysis, requires an NPV analysis to find the correct transformations. It is comforting though that for this class of models the traditional average cost models can still be applied.

# 5 Multi-source systems

Until now we only considered situations in which inventories consist of products that all have generated the same cash-flows. Additional problems may arise if inventories consist of products that have been produced in different ways against different costs. This is the case with products that can be both newly manufactured and remanufactured from old products. Remanufactured products have the same functionality and quality as newly produced products and can therefore be sold at the same market for the same price. In this sense they are indistinguishable and can be put in the same inventory. However, the cash flows generated by manufactured products are different from remanufactured products, since they follow from different processes with different costs. In this section we show how this affects the difference between NPV and AC.

## 5.1 A system with manufacturing and remanufacturing

Consider a two source system (Figure 5.1), where product demand can be fulfilled both by manufactured products, with marginal cost $c_m$ and fixed set-up cost $K_m$, and remanufactured products, with marginal cost $c_r$ and fixed set-up cost $K_r$. Manufactured and remanufactured products have the same quality standards and are sold on the same market against the same price $p$. The main difference between the manufacturing process and remanufacturing process is that the latter depends on the flow of product returns, which for now is assumed to be deterministic with rate $\gamma$, $0 < \gamma < \lambda$.

This system was first proposed by Schrady (1967) and further analyzed by Richter (1996) and Teunter (1998). In the above-mentioned papers the system is controlled by subsequently producing $N$ manufacturing batches and $M$ remanufacturing batches. For ease of explanation we assume here that $N = M = 1$ so that the system is controlled by repeatedly producing one manufacturing batch of size $Q_m$, succeeded by one remanufacturing batch of size $Q_r$.[2] We as-

[2] The following analysis is easily extended to arbitrary $N$ and $M$, but this would only lengthen the mathematical

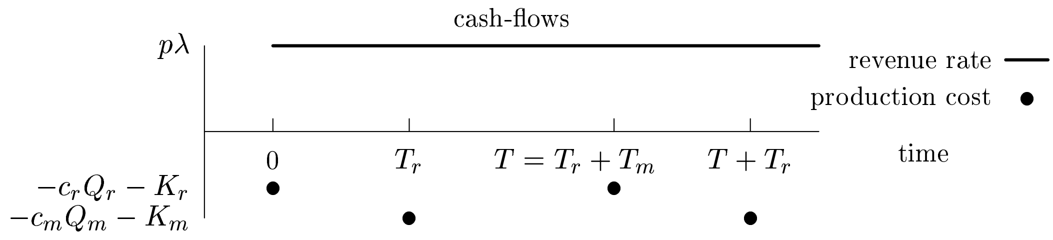


**Figure 5.2** Relevant cash-flows for the two-source system without disposal.

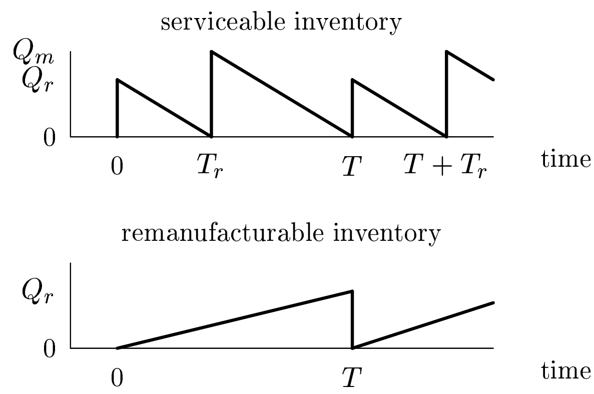


**Figure 5.3** The inventory processes of a two-source system.

sume that at time 0 we start with zero inventory of both serviceables and remanufacturables. Thus, to start up the system and to guarantee a monotonous ordering strategy at the same time, we have to start with a manufacturing batch of size $Q_r$. The first manufacturing batch of size $Q_m$ then occurs at time $T_r = Q_r/\lambda$ and the first remanufacturing batch occurs at time $T = (Q_m + Q_r)/\lambda$. Continuing this way, manufacturing batches and remanufacturing batches occur every $T$ time units. Leadtimes are assumed to be zero. Note that, since all returns are used for remanufacturing, we have $Q_r = \gamma T$, $Q_m = (\lambda - \gamma)T$ and $Q_r = \frac{\gamma}{\lambda-\gamma} Q_m$. The timing of all relevant cash-flows is visualized in Figure 5.2.

The $AS_v$ for this system reads

$$\begin{aligned} AS_v &= p\lambda - r\left(Q_r c_m + \frac{Q_m c_m \mathrm{e}^{-rT_r} + Q_r c_r \mathrm{e}^{-rT}}{1 - \mathrm{e}^{-rT}}\right) \\ &\approx (p\lambda - c_m(\lambda - \gamma) - c_r\gamma) - r c_m Q_m \left(\tfrac{1}{2} - \tfrac{\gamma}{\lambda}\right) - r\left(c_m - c_r/2\right) Q_r. \end{aligned} \tag{10}$$

Again, the first term denotes the total marginal profits and the last two terms denote the total opportunity costs of inventory investment.

Let's now compare the above expression with the corresponding average profit function. Figure 5.3 depicts the inventory process of serviceables and remanufacturables, from which we derive

expressions without gaining additional insight.

that the long run average inventory of remanufactured products equals $Q_r T_r/(2T) = (\gamma/\lambda)Q_r/2$, the long run average inventory of manufactured products equals $Q_m(T - T_r)/(2T) = (1 - \gamma/\lambda)Q_m/2$, and the average inventory of remanufacturable products equals $Q_r/2$. This leads to the following average profit function:

$$AP_v = (p\lambda - c_m(\lambda - \gamma) - c_r\gamma) - h_m\left(1 - \tfrac{\gamma}{\lambda}\right)Q_m/2 - h_r\left(\tfrac{\gamma}{\lambda}\right)Q_r/2 - h_n Q_r/2. \tag{11}$$

Clearly, both opportunity costs and average inventory are linear in $Q_m$ and $Q_r$ so that $h_m$, $h_r$, and $h_n$ can be chosen such that (11) is equivalent to (10). Since the average inventory of remanufactured products and the average inventory of remanufacturables are both linear in $Q_r$, either $h_r$ or $h_n$ is redundant. Naturally we choose $h_n = 0$ because there are no investments in remanufacturable inventory and thus no associated opportunity cost exist. This gives

$$\begin{aligned} h_m &\rightarrow rc_m\left(\tfrac{\lambda}{\lambda-\gamma}\right) \\ h_r &\rightarrow rc_r\left(2 - \tfrac{\lambda}{\gamma}\right) \\ h_n &\rightarrow 0\,. \end{aligned}$$

So, setting $h_n = 0$ leads to different holding cost rates for manufactured and remanufactured products. This is rather counter-intuitive and may lead to the (false) conclusion that in fulfilling product demands priority should be given to either manufactured or remanufactured products, whichever generates more opportunity costs. That this conclusion is false can be clearly seen when we look at it from an NPV perspective. The financial consequences of selling either a manufactured item or a remanufactured item are exactly the same, since they generate the *same cash inflow* at the *same time*.

These counter-intuitive results can be avoided by choosing the same holding cost rates for manufactured and remanufactured products. This gives

$$\begin{aligned} h_m &\rightarrow rc_m \\ h_r &\rightarrow rc_m \\ h_n &\rightarrow r(c_m - c_r)\,. \end{aligned}$$

What about the set-up costs? The $AS_f$ is derived as

$$\begin{aligned} AS_f &= -r\left(K_m + \frac{K_m \mathrm{e}^{-rT_r} + K_r \mathrm{e}^{-rT}}{1 - \mathrm{e}^{-rT}}\right) \\ &\approx -(\lambda - \gamma)K_m/Q_m - \gamma K_r/Q_r - rK_m\left(\tfrac{3}{2} - \tfrac{\gamma}{\lambda}\right) + rK_r/2, \end{aligned} \tag{12}$$

and we observe that the opportunity costs of set-ups do not depend on the policy parameters. This however will change in the next section.

Our framework shows that the only way to influence the opportunity costs of holding inventories is to somehow change the *timing* of the investments $c_m$ and $c_r$, for instance by using pull and push type policies (see van der Laan *et al.*, 1998), or to somehow change the *fraction* of (re)manufactured products by using a disposal policy (see e.g. Inderfurth, 1997; van der Laan and Salomon, 1997). In the next paragraph we extend the manufacturing/remanufacturing model with the option to dispose product returns.

## 5.2 A system with manufacturing, remanufacturing, and disposal

A number of authors have considered disposal strategies in a manufacturing/remanufacturing environment in order to optimize total system costs (e.g. Heyman, 1977; Inderfurth, 1997; Richter,1996; Simpson, 1978; van der Laan, 1997). However, doing so, care should be taken in the modeling process. Including the disposal option enables to influence the throughput of the manufacturing and remanufacturing process. From Section 3.1 we have learned that when the throughput of the system depends on policy parameters, the traditional average costs approach may not be appropriate.

Consider the example of Section 5.1, but instead of remanufacturing all product returns we decide to use only a fraction $U$, $0 \leq U \leq 1$, and continuously dispose a fraction $1 - U$. The unit 'cost' related to disposal, $c_d$ can be positive (for instance if products contain hazardous materials, which need to be processed in an environmental friendly manner), or negative (for instance if product returns have a positive salvage value and can be sold to a third party). Define the decision variable $\Gamma = U\gamma$, then the total amount of disposals during a production cycle of length $T$ equals $(\gamma - \Gamma)T$.

The $AS_v$ for the situation with continuous disposals is

$$\begin{aligned} AS_v &= p\lambda - (\gamma - \Gamma)c_d - r\left(Q_r c_m + \tfrac{Q_m c_m \mathrm{e}^{-rT_r} + Q_r c_r \mathrm{e}^{-rT}}{1-\mathrm{e}^{-rT}}\right) \\ &\approx (p\lambda - c_m(\lambda - \Gamma) - c_r\Gamma - c_d(\gamma - \Gamma)) \\ &\quad -rc_m Q_m\left(\tfrac{1}{2} - \tfrac{\Gamma}{\lambda}\right) - r\left(c_m - c_r/2\right)Q_r \ . \end{aligned}$$

The parameter $c_d$ only appears in the marginal cost term so there are no opportunity costs associated with product disposal.

If $c_d > 0$, it is more efficient from a financial point of view to dispose as late as possible. One could choose to dispose a batch of remanufacturables whenever a certain capacity limit has been reached. Here, we choose to accumulate the products to be disposed and dispose them all at once whenever a remanufacturing batch is initiated, i.e. at time $T_m$, $T + T_m$, and so on. The amount disposed at the end of each cycle equals $(\gamma - \Gamma)T$. The $AS_v$ for batch-disposals thus reads

$$\begin{aligned} AS_v &= p\lambda - r\left(Q_r c_m + \tfrac{Q_m c_m \mathrm{e}^{-rT_r} + (Q_r c_r + (\gamma-\Gamma)T c_d)\mathrm{e}^{-rT}}{1-\mathrm{e}^{-rT}}\right) \\ &\approx (p\lambda - c_m(\lambda - \Gamma) - c_r\Gamma - c_d(\gamma - \Gamma)) \\ &\quad -rc_m Q_m\left(\tfrac{1}{2} - \tfrac{\Gamma}{\lambda}\right) - r\left(c_m - c_r/2\right)Q_r + rc_d(Q_m + Q_r)\left(\tfrac{\gamma-\Gamma}{2\lambda}\right) \ . \end{aligned} \tag{13}$$

Note the opportunity cost/yield related to disposal, $rc_d(Q_m + Q_r)\left(\frac{\gamma-\Gamma}{2\lambda}\right)$.

The annuity stream due to (re)manufacturing set-ups is derived as

$$\begin{aligned} AS_f &= -r\left(K_m + \frac{K_m \mathrm{e}^{-rT_r} + K_r \mathrm{e}^{-rT}}{1 - \mathrm{e}^{-rT}}\right) \\ &\approx -(\lambda - \Gamma)K_m/Q_m - \Gamma K_r/Q_r - rK_m\left(\tfrac{3}{2} - \tfrac{\Gamma}{\lambda}\right) + rK_r/2. \end{aligned} \tag{14}$$

We observe that the opportunity costs of set-ups depend on the policy parameter $\Gamma$, and can no longer be ignored (Compare with (12)).

Combining (13) and (14) we find that for $0 < \Gamma < \lambda$ the total annuity stream is given by

$$AS = p\lambda - r\left(K_m + Q_r c_m + \frac{(K_m + Q_m c_m)\mathrm{e}^{-rT_r} + (K_r + Q_r c_r + (\gamma - \Gamma)\, T c_d)\mathrm{e}^{-rT}}{1 - \mathrm{e}^{-rT}}\right), \quad (15)$$

which can be approximated by the function

$$\begin{aligned} \overline{AS} \;=\; & p\lambda - c_m(\lambda - \Gamma) - c_r\Gamma - c_d(\gamma - \Gamma) \\ & -(\lambda - \Gamma)K_m/Q_m - \Gamma K_r/Q_r \\ & -rK_m - r(K_m + c_m Q_m)\left(\tfrac{1}{2} - \tfrac{\Gamma}{\lambda}\right) + rK_r/2 - r(c_m - c_r/2)Q_r \\ & +rc_d(Q_m + Q_r)\left(\tfrac{\gamma - \Gamma}{2\lambda}\right) . \end{aligned} \quad (16)$$

The traditional AC approach calculates the total average profit function as the total marginal profits, set-up costs, and inventory costs as

$$\begin{aligned} AP \;=\; & p\lambda - c_m(\lambda - \Gamma) - c_r\Gamma - c_d(\gamma - \Gamma) \\ & -(\lambda - \Gamma)K_m/Q_m - \Gamma K_r/Q_r \\ & -h_m(1 - \tfrac{\Gamma}{\lambda})Q_m/2 - h_r\left(\tfrac{\Gamma}{\lambda}\right)Q_r/2 - h_n\left(\tfrac{\gamma}{\lambda}\right)(Q_m + Q_r)/2. \end{aligned} \quad (17)$$

Using the relation $Q_r = \frac{\Gamma}{\lambda - \Gamma} Q_m$ it is easily verified that we can transform AP into $\overline{AS}$ (up to a constant), by using the following transformations of $c_r$, $h_m$, $h_r$, and $h_n$:

$$\begin{aligned} c_m &\rightarrow c_m + rK_m/\lambda \\ h_m &\rightarrow rc_m \\ h_r &\rightarrow rc_m \\ h_n &\rightarrow r(c_m - c_r - (1 - \Gamma/\gamma)c_d) \end{aligned} \quad (18)$$

Clearly, this is a non-linear transformation in the decision variable $\Gamma$, which indicates the considerable gap between the traditional average cost approach and the linearization of the annuity stream. This is further illustrated by some analytical and numerical results in the next section.

# 6 Analytical and numerical comparison of alternative transformations

Consider the inventory system with manufacturing, remanufacturing, and batch-disposal of Section 5.2. In this section we investigate how the average cost approach performs with respect to the linearization of the annuity stream approach, when forcing a linear transformation of the cost parameters that does not depend on decision variables.

Since demand is either fulfilled by manufacturing or remanufacturing and the number of (re)-manufacturing batches within production cycle $T$ is fixed to one, we have $Q_r = \frac{\Gamma}{\lambda-\Gamma} Q_m$. Hence, for $0 < \Gamma \leq \gamma < \lambda$ expressions (15) – (17) can be transformed into functions of $Q_m$ and $\Gamma$ only. For the special case $\Gamma = 0$ similar expressions are derived in the appendix. For all the numerical examples in this section we use the base-case scenario of Table 1, unless specified otherwise.

| parameter | $\lambda$ | $\gamma$ | $p$ | $c_m$ | $c_r$ | $c_d$ | $K_m$ | $K_r$ | $r$ |
|---|---|---|---|---|---|---|---|---|---|
| value | 20 | 10 | 20 | 10 | 5 | 5 | 10 | 10 | 0.10 |

**Table 1** Base case scenario

As a performance measure for batch size $Q$ we define the relative difference

$$R(Q) = \left[1 - \frac{\tilde{AS}(Q)}{\tilde{AS}(Q^{\mathrm{AS}})}\right] \times 100\%,$$

where $\tilde{AS}(.) = AS(.) - (p\lambda - c_m(\lambda - \gamma) - c_r\gamma)$ is the relevant annuity stream and $Q^{\mathrm{AS}}$ is the batch-size that maximizes $AS(.)$.

In our analysis we consider two transformations.

**Transformation A**

An intuitive, though rather naive, transformation is the following:

$$\begin{aligned} h_m &\to rc_m \\ h_r &\to rc_r \\ h_n &\to 0 \end{aligned}$$

The above choice follows from the (false) intuition that opportunity costs of inventory investment are (approximately) equal to the interest rate times the average inventory investment. Parameter $c_r$ is chosen according to (18)) to take the opportunity cost of remanufacturing batches into account:

$$c_m \to \begin{cases} c_m + rK_m/\lambda, & \text{if } \Gamma > 0 \\ c_m, & \text{otherwise} \end{cases} \tag{19}$$

**Transformation B**

A seemingly more sophisticated transformation of $h_m$, $h_r$, and $h_n$ was proposed by Inderfurth and Teunter (1998) on the basis of a heuristic argument: "The money tied up in a non-serviceable item is $-cd$, since that could have been 'earned' by disposing of it. Hence, $h_n = r(-c_d)$ (...). The money tied up in a remanufactured item is that tied up in a non-serviceable item plus the cost $c_r$

of remanufacturing the item. Hence, $h_r = r(c_r - c_d)$ (...). The money tied up in a manufactured item is simply the cost $c_m$ of manufacturing an item. Hence, $h_m = rc_m$." Summarizing:

$$
\begin{aligned}
h_m &\rightarrow rc_m \\
h_r &\rightarrow r(c_r - c_d) \\
h_n &\rightarrow -rc_d
\end{aligned}
$$

Parameter $c_r$ is chosen according to (19) to take the opportunity cost of remanufacturing batches into account. Note that for $c_d = 0$ *Transformation A* and *Transformation B* are equivalent.

To compare the various approaches, we consider two cases.

**Case 1:** $\Gamma = 0$

If $\Gamma = 0$ the difference between $\overline{AS}$ and AP is given by

$$\overline{AS} - AP = \left[h_m - rc_m + (h_n + rc_d)\left(\frac{\gamma}{\lambda}\right)\right] Q_m/2 - rK_m/2 \qquad (20)$$

where the last term is just a constant but the first term depends on $Q_m$. If *Transformation B* is applied the first term vanishes, hence the two approaches are equal up to a constant. For *Transformation A* however the righthand side of (20) equals

$$rc_d\left(\frac{\gamma}{\lambda}\right) Q_m/2 - rK_m/2$$

Thus under *Transformation A* the two approaches will differ significantly for large enough $|c_d|$ (see Table 2).

| | | | | | Transform. A | | Transform. B | |
|---|---|---|---|---|---|---|---|---|
| $c_d$ | $Q_m^{\mathrm{AS}}$ | $\tilde{AS}(Q_m^{\mathrm{AS}})$ | $Q_m^{\overline{\mathrm{AS}}}$ | $R(Q_m^{\overline{\mathrm{AS}}})$ | $Q_m^{\mathrm{AP}}$ | $R(Q_m^{\mathrm{AP}})$ | $Q_m^{\mathrm{AP}}$ | $R(Q_m^{\mathrm{AP}})$ |
| -15 | 15.1 | 73.01 | 15.1 | 0.0 | 20.0 | 1.5 | 15.1 | 0.0 |
| -10 | 16.3 | 24.94 | 16.3 | 0.0 | 20.0 | 2.1 | 16.3 | 0.0 |
| -5 | 17.7 | -22.97 | 17.9 | 0.0 | 20.0 | -0.7 | 17.9 | 0.0 |
| 0 | 19.7 | -70.67 | 20.0 | 0.0 | 20.0 | 0.0 | 20.0 | 0.0 |
| 5 | 22.4 | -118.10 | 23.1 | 0.0 | 20.0 | -0.1 | 23.1 | 0.0 |
| 10 | 26.6 | -165.12 | 28.3 | 0.0 | 20.0 | -0.4 | 28.3 | 0.0 |
| 15 | 33.8 | -211.49 | 40.0 | -0.1 | 20.0 | -0.9 | 40.0 | -0.1 |

**Table 2** Performance of $Q_m^{\overline{\mathrm{AS}}}$ and $Q_m^{\mathrm{AP}}$ under the base-case scenario for $\Gamma = 0$ and various values of $c_d$.

**Case 2:** $\Gamma = \gamma$

If $\Gamma = \gamma$ the difference between $\overline{AS}$ and AP is given by

$$\overline{AS} - AP = \left[h_m\left(1 - \tfrac{\gamma}{\lambda}\right) - rc_m\left(\tfrac{1}{2} - \tfrac{\gamma}{\lambda}\right)\right] Q_m/2$$

$$+ \left[h_r\left(\tfrac{\gamma}{\lambda}\right) - r(2c_m - c_r) + h_n\right] Q_r/2 - rK_m\left(\tfrac{3}{2} - \tfrac{\gamma}{\lambda}\right) + rK_r/2\ . \tag{21}$$

Under *Transformation A* the righthand side of (21) reduces to

$$r(c_r - c_m)\left(\frac{\gamma}{\lambda}\right)\left(\frac{\lambda+\gamma}{\lambda-\gamma}\right) Q_m/2 - rK_m\left(\frac{3}{2} - \frac{\gamma}{\lambda}\right) + rK_r/2.$$

The difference will be significant for large enough $|c_m - c_r|$ and/or $\gamma$ (see Table 3 and 4).

| | | | | | Transform. A | | Transform. B | |
|---|---|---|---|---|---|---|---|---|
| $c_r$ | $Q_m^{\mathrm{AS}}$ | $\tilde{AS}(Q_m^{\mathrm{AS}})$ | $Q_m^{\overline{\mathrm{AS}}}$ | $R(Q_m^{\overline{\mathrm{AS}}})$ | $Q_m^{\mathrm{AP}}$ | $R(Q_m^{\mathrm{AP}})$ | $Q_m^{\mathrm{AP}}$ | $R(Q_m^{\mathrm{AP}})$ |
| 0 | 14.2 | -28.71 | 14.1 | 0.0 | 28.3 | -23.8 | $\infty^{a)}$ | $-\infty$ |
| 5 | 16.3 | -25.00 | 16.3 | 0.0 | 23.1 | -6.0 | $\infty^{a)}$ | $-\infty$ |
| 10 | 19.7 | -20.67 | 20.0 | 0.0 | 20.0 | 0.0 | 40.0 | -26.7 |
| 15 | 26.1 | -15.27 | 28.3 | -0.3 | 17.9 | -7.5 | 28.3 | -0.3 |
| 20 | 43.1 | - 7.47 | $\infty^{a)}$ | $-\infty$ | 16.3 | -75.5 | 23.1 | -31.6 |

**Table 3** Performance of $Q_m^{\overline{\mathrm{AS}}}$ and $Q_m^{\mathrm{AP}}$ under the base-case scenario for $\Gamma = \gamma$ and various values of $c_r$. a) The objective function is an increasing function in $Q_m$.

| | | | | | Transform. A | | Transform. B | |
|---|---|---|---|---|---|---|---|---|
| $\gamma$ | $Q_m^{\mathrm{AS}}$ | $\tilde{AS}(Q_m^{\mathrm{AS}})$ | $Q_m^{\overline{\mathrm{AS}}}$ | $R(Q_m^{\overline{\mathrm{AS}}})$ | $Q_m^{\mathrm{AP}}$ | $R(Q_m^{\mathrm{AP}})$ | $Q_m^{\mathrm{AP}}$ | $R(Q_m^{\mathrm{AP}})$ |
| 0 | 19.7 | -20.67 | 20.0 | 0.0 | 20.0 | 0.0 | 20.0 | 0.0 |
| 5 | 24.5 | -25.27 | 24.5 | 0.0 | 27.5 | -0.6 | 32.1 | -3.6 |
| 10 | 16.3 | -25.00 | 16.3 | 0.0 | 23.1 | -6.0 | $\infty^{a)}$ | $-\infty$ |
| 15 | 7.0 | -28.66 | 7.1 | 0.0 | 12.1 | -15.4 | $\infty^{a)}$ | $-\infty$ |
| 19 | 1.2 | -33.42 | 1.2 | 0.0 | 2.1 | -16.6 | $\infty^{a)}$ | $-\infty$ |

**Table 4** Performance of $Q_m^{\overline{\mathrm{AS}}}$ and $Q_m^{\mathrm{AP}}$ under the base-case scenario for $\Gamma = \gamma$ and various values of $\gamma$. $^{a)}$ The objective function is an increasing function in $Q_m$.

Under *Transformation B* the righthand side of (21) reduces to

$$r(c_r - c_m - c_d)\left(\frac{\gamma}{\lambda}\right)\left(\frac{\lambda+\gamma}{\lambda-\gamma}\right) Q_m/2 - rK_m\left(\frac{3}{2} - \frac{\gamma}{\lambda}\right) + rK_r/2.$$

The difference will be significant for large enough $|c_m + c_d - c_r|$, $\gamma$, and/or $|c_d|$ (see Table 3,4, and 5).

## 7 Discussion

Although the net present value approach is the more appropriate framework, average cost models are dominating the field of inventory control and production planning. In this paper we have shown that the traditional average cost approach, which does not make a distinction between opportunity costs of holding inventories and physical inventory costs, leads to reasonable results

| $c_d$ | $Q_m^{\mathrm{AS}}$ | $\tilde{AS}(Q_m^{\mathrm{AS}})$ | $Q_m^{\overline{\mathrm{AS}}}$ | $R(Q_m^{\overline{\mathrm{AS}}})$ | Transform. A $Q_m^{\mathrm{AP}}$ | Transform. A $R(Q_m^{\mathrm{AP}})$ | Transform. B $Q_m^{\mathrm{AP}}$ | Transform. B $R(Q_m^{\mathrm{AP}})$ |
|---|---|---|---|---|---|---|---|---|
| -15 | 16.3 | -25.00 | 16.3 | 0.0 | 23.1 | -6.0 | 11.5 | - 6.1 |
| -10 | 16.3 | -25.00 | 16.3 | 0.0 | 23.1 | -6.0 | 13.3 | -2.1 |
| -5 | 16.3 | -25.00 | 16.3 | 0.0 | 23.1 | -6.0 | 16.3 | 0.0 |
| 0 | 16.3 | -25.00 | 16.3 | 0.0 | 23.1 | -6.0 | 23.1 | -6.0 |
| 5 | 16.3 | -25.00 | 16.3 | 0.0 | 23.1 | -6.0 | $\infty^{a)}$ | $-\infty$ |
| 10 | 16.3 | -25.00 | 16.3 | 0.0 | 23.1 | -6.0 | $\infty^{a)}$ | $-\infty$ |
| 15 | 16.3 | -25.00 | 16.3 | 0.0 | 23.1 | -6.0 | $\infty^{a)}$ | $-\infty$ |

**Table 5** Performance of $Q_m^{\overline{\mathrm{AS}}}$ and $Q_m^{\mathrm{AP}}$ under the base-case scenario for $\Gamma = \gamma$ and various values of $c_d$.
a) The objective function is an increasing function in $Q_m$.

for single-source systems, but not necessarily for multi-source systems. The NPV approach does make a clear distinction between physical inventory costs and opportunity costs, since the two are not directly related. The latter does not depend on physical stocks at all, but only on the amount and timing of the investments.

The traditional approach only takes the opportunity costs of *holding inventories* into account, but this should not be a general rule. All cash-flows generate opportunity costs or yields that cannot be disregarded if the cash-flows depend on decision parameters. For example, in a manufacturing/remanufacturing system with disposal the throughput of the (re)manufacturing process is controlled by a decision variable. In that case also opportunity costs of set-ups and disposals should be taken into account. Clearly, these opportunity costs have got little to do with physical inventories.

Main conclusion of this paper is that basically there are two classes of models: a class for which a holding cost transformation exists that does not depend on decision variables, such that NPV coincides with AC (up to a constant), and a class for which such a transformation does not exist. A typical example of the latter class is a system with manufacturing, remanufacturing, and batch disposal.

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## Appendix

If $\Gamma = 0$ there are no cash-flows related to remanufacturing operations. Hence, expressions (15) – (17) are given as

$$AS = p\lambda - r\left(\frac{K_m + Q_m c_m + \left(\frac{\gamma}{\lambda}\right) Q_m c_d \mathrm{e}^{-rQ_m/\lambda}}{1 - \mathrm{e}^{-rQ_m/\lambda}}\right),$$

$$\overline{AS} = p\lambda - c_m\lambda - c_d\gamma - \lambda K_m/Q_m - r(K_m + c_m Q_m)/2 + rc_d\left(\frac{\gamma}{\lambda}\right)Q_m/2,$$

and

$$AP = p\lambda - c_m\lambda - c_d\gamma - \lambda K_m/Q_m - h_m Q_m/2 - h_n\left(\frac{\gamma}{\lambda}\right)Q_m/2.$$

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