MANAGEMENT SCIENCE
Vol. 51, No. 7, July 2005, pp. 1032–1045
ISSN 0025-1909 | EISSN 1526-5501 | 05 | 5107 | 1032

DOI 10.1287/mnsc.1050.0360

Incentives for Efficient Inventory Management: The Role of Historical Cost

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This paper examines inventory management from an incentive perspective. We show that when a manager has private information about future attainable revenues, the residual income performance measure based on historical cost can achieve optimal (second-best) incentives with regard to managerial effort as well as production and sales decisions. The LIFO (last-in–first-out) inventory flow rule is shown to be preferable to the FIFO (first-in–first-out) rule for the purpose of aligning incentives. Our analysis also finds support for the lower-of-cost-or-market inventory-valuation rule in situations where the manager receives new information after the initial contracting stage.

Key words: inventory management; historical cost accounting; decentralization; agency theory
History: Accepted by William S. Lovejoy, operations and supply chain management; received December 2003. This paper was with the authors 3 months for 1 revision.

1. Introduction

The question of how much inventory a firm should keep has been studied extensively in the operations management literature. For the most part, this literature has ignored management control issues and instead adopted a centralized perspective wherein a planner seeks to formulate an optimal inventory policy for a given information structure.[1] This paper studies inventory management from an incentive and control perspective when a manager has superior information and his productive effort affects future sales revenues. The firm's objective is to maximize the present value of expected cash flows net of the manager's compensation. By the Revelation Principle, it is optimal to adopt a centralized structure in which all decisions are made in response to the manager's reported information. In practice, of course, delegation of decision making is common. We examine whether simple inventory-valuation rules based on historical cost information can achieve *efficient delegation*, that is, whether delegation of decision making combined with managerial performance measures based on historical cost can create optimal incentive provisions.

Consider a representative product that is manufactured and sold over multiple periods. At the outset, a manager has superior information about future sales revenues. The presence of capacity constraints requires the firm to hold inventory over a certain period of time. Even though the owner ultimately cares about the stream of discounted cash flows, performance measurement is usually based on accounting data. We provide a justification for this practice by showing that performance measures based on the entire *history* of cash flows are generally incapable of aligning the objectives of owners and managers. The main impediment to cash-flow-based contracting is not lack of memory, a claim often found in the literature, but the impossibility of achieving proper intertemporal matching of costs and revenues. Accrual accounting, in contrast, facilitates such matching.

A commonly used accounting-based performance measure is income calculated on the basis of historical cost. Under generally accepted accounting principles (GAAP), the production cost of inventory is not included in income until such time as the inventory is sold. Instead, the firm records these production costs as an asset on the balance sheet. In contrast, inventory holding costs are expensed as incurred under GAAP. It is well known that accounting income ignores the time value of money and therefore may create incentives to overproduce. This bias can be corrected via the residual income performance metric, which effectively subtracts an interest charge for the value of all operating assets, including inventory. We find that residual income can achieve efficient delegation, provided the firm adopts a *compounded* historical cost valuation rule whereby (i) production and holding

[1] See, for instance, Porteus (1990) and Nahmias (1992).

costs are capitalized, and (ii) inventory is treated as an interest-accruing asset. The resulting performance measure will be unaffected by any buildup of inventory, yet the manager is charged the real, i.e., compounded, production cost at the time the inventory is sold.

Ending inventory in each period typically contains output units that were produced in different periods and hence carry different historical costs. Firms therefore specify an inventory "flow rule" (e.g., LIFO, FIFO). The LIFO (last-in–first-out) rule first expenses the most recently produced inventory units, whereas the FIFO (first-in–first-out) rule first expenses the oldest units.[2] Because in our setting the demand for inventory arises from capacity constraints in some periods, the marginal cost of a unit sold is the compounded unit cost of the last period with unconstrained capacity. Under certain conditions, residual income based on compounded historical cost and the LIFO rule yields a cost charge equal to the relevant cost, and thus results in efficient delegation. In contrast, we find the FIFO rule to be incapable of aligning the cost charges for units in inventory with the relevant cost.

In many situations of interest, managers receive updated information about future revenues after the initial production decision. Such additional forecast information further complicates the delegation problem. Initially, the manager should internalize the expected future benefits and costs from building up inventory. On the other hand, the subsequent inventory-depletion policy should treat all historic costs as sunk. For products with short (two-period) life cycles, we show that the lower-of-cost-or-market valuation rule creates the desired incentives. According to this rule, units in inventory at the end of the second period are written down to the prevailing market price if that price is below historical cost. While this valuation rule is sometimes criticized for its undue conservatism, we identify environments where it has desirable incentive properties. With sequential information arrival and longer product life cycles, however, it becomes impossible to achieve efficient outcomes when the managerial performance measure is based on accounting information. This impossibility reflects that a successful performance measure would have to straddle two conflicting objectives: (i) the inventory should be written down because the costs incurred are sunk; (ii) the inventory value should reflect the opportunity cost of sales in any given period, i.e., foregone future revenues.

Our paper adds to a growing literature that examines alternative accrual accounting and asset-valuation rules from a managerial control perspective.[3] While the earlier studies in Rogerson (1997) and Reichelstein (1997) focused on depreciation schedules and their impact on managers' investment incentives, subsequent literature has broadened this line of research to other transactions.[4] Common to these papers is that matching of revenues and expenses generates proper measures of periodic performance. Such matching requires the designer (or an accountant working on his behalf) to have forward-looking information regarding the intertemporal pattern of future cash flows. In contrast, the inventory valuation rules identified in this paper do not need to be forward looking. To achieve proper matching, it suffices to carry the inventory asset at (compounded) historical cost without any knowledge of future revenues. The informational requirements for delegating inventory management decisions to a better-informed manager thus are considerably lower than those for delegating investment decisions in capital assets.[5]

The paper most closely related to ours is Dutta and Zhang (2002). They examine revenue recognition in a setting where output produced in one period is sold in the next period.[6] In contrast to their results, we show that historical cost accounting can achieve efficient delegation even in settings where managers control the timing of sales over arbitrary planning horizons.

[2] The accounting literature on the LIFO/FIFO choice has been primarily concerned with tax issues (e.g., Dopuch and Pincus 1988, Hughes and Schwartz 1988), but has generally ignored management control issues.

[3] In recent years, management consultants have proposed a variety of accounting-based performance measures under the umbrella of so-called economic profit plans, e.g., economic value added (EVA). Furthermore, EVA proponents such as Ehrbar and Stewart (1999) and Young and O'Byrne (2001) have proposed "adjustments" to the accounting rules used for external financial reporting purposes (i.e., GAAP rules). Ittner and Larcker (1998) survey recent developments in the area of performance measurement.

[4] Baldenius and Ziv (2003) consider corporate income taxes and sequential uncertainty resolution. Wei (2004) addresses fixed-cost allocations when investments by one division benefit other divisions, and Bareket (2004) and Mohnen (2004) introduce budget constraints. Moving beyond the framework of goal-congruent performance measures, Mishra and Vaysman (2000), Reichelstein (2000), Dutta and Reichelstein (2002), Dutta and Zhang (2002), Baldenius (2003), and Wagenhofer (2003) have added explicit agency costs and the question of optimal second-best mechanisms to this line of research.

[5] One way to view the difference between the two settings is to think of investment in fixed assets as a "public good" that generates benefits in multiple future periods. In contrast, a unit of finished-goods inventory may be viewed as a "private good" generating a benefit only in the period in which it is sold.

[6] Dutta and Zhang (2002) study a so-called LEN moral-hazard model (linear contracts, exponential utilities, and normal noise terms) in which the product can effectively be sold at only one point in time. Consistent with our findings, they also find that the lower-of-cost-or-market rule is optimal for products with a two-period life cycle.

The remainder of the paper is organized as follows. Following the description of the model in §2, §3 derives incentive-compatible performance measures based on accounting information. Section 4 generalizes the model by allowing for the possibility that the manager learns updated forecast information after making the initial production decision. We decompose the problem of efficient delegation into two steps. Sections 2–4 take as exogenously given the manager's private information regarding the productivity of future sales. This part of the paper abstracts from moral-hazard considerations and instead focuses on goal-congruent performance measures. In §5, the manager is assumed to take unobservable (and personally costly) actions that jointly with the underlying state information determine the productivity of future sales. The nature of the agency problem we study exhibits sufficient separability so that the performance measures identified in §§3 and 4 will also enable efficient delegation once explicit agency costs are taken into account. We conclude in §6.

2. The Model

A manager makes production and sales decisions on behalf of a principal. The product has a life cycle of T periods. The resulting sales revenues are affected by productivity parameters, denoted by $(z_1, \ldots, z_T)$, which are known to the manager but not the principal. Initially, we take these parameters as given and search for delegation schemes that provide the manager with incentives to choose production and sales quantities that are optimal conditional on $(z_1, \ldots, z_T)$.

If the firm produces q_t units and sells s_t units in period $t \in \{1, \ldots, T\}$, ending inventory in period t is

$$x_t \equiv \sum_{i=1}^{t} (q_i - s_i),$$

with $x_0 = 0$. Let r denote the firm's (positive) discount rate and $\gamma \equiv (1+r)^{-1}$ the corresponding discount factor. The unit production cost equals c and is assumed to be constant across periods.[7] Time value of money considerations thus would call for zero inventory absent any capacity constraints. Feasibility of a production and sales plan, however, requires that for all periods t,

$$(s_t, q_t) \in F_t(x_{t-1}) \equiv \{(s_t, q_t) \mid 0 \le q_t \le \bar{q}_t \text{ and } s_t \le q_t + x_{t-1}\}, \quad (1)$$

with $\bar{q}_t$ as the available production capacity in period t. Cash flow in t equals

$$CF_t(q_t, s_t \mid z_t) \equiv R_t(s_t \mid z_t) - cq_t - kx_t,$$

where k is the inventory holding cost per unit (e.g., warehousing, spoilage). The function $R_t(s_t \mid z_t)$ describes revenues as a function of the sales quantity, with z_t denoting that period's sales productivity parameter. The functions $R_t(\cdot \mid z_t)$ are assumed to be strictly concave in s_t for any z_t. We use the vector notation: $q \equiv (q_1, \ldots, q_T)$, $s \equiv (s_1, \ldots, s_T)$, and $z \equiv (z_1, \ldots, z_T)$.

Taking the productivity parameters z as exogenously given, we first characterize the production and sales plan the principal would choose conditional on z. Such a plan solves the following program:

$$\mathcal{P}^*(z): \quad \max_{q,s} \sum_{t=1}^{T} \gamma^t CF_t(q_t, s_t \mid z_t), \quad \text{subject to (1).}$$

Let $(q^*(z), s^*(z))$ denote the solution to program $\mathcal{P}^*(z)$. We refer to this solution as the *z-efficient production and sales plan*. Our analysis is confined to product life cycles for which the solution to $\mathcal{P}^*(z)$ involves only one inventory cycle. Specifically, the firm is capacity constrained only over one time interval. The z-efficient production and sales plan then satisfies the following two conditions:

$$q_t^*(z) = \bar{q}_t, \quad t \in I \equiv \{\tau+1, \ldots, \hat{\tau}\},$$
$$q_t^*(z) < \bar{q}_t, \quad t \notin I.$$

Thus, it is commonly known that the inventory buildup should begin in period τ, the last unconstrained period preceding the inventory cycle I.[8] Capacity in period τ is assumed sufficient to accommodate production of concurrent sales and of those units intended for sale during I; that is, $\bar{q}_\tau \ge s_\tau^*(z) + \sum_{i \in I} [s_i^*(z) - \bar{q}_i]$. In any period $t < \tau$ and $t \ge \hat{\tau}$, the firm produces only for concurrent sales.

To characterize the solution to the z-efficient production and sales plan, we introduce notation for the relevant (production and holding) cost, evaluated in period j, of a unit produced in period i and sold in period $j > i$:

$$d_{ij} \equiv (1+r)^{j-i} c + \sum_{l=1}^{j-i} (1+r)^l k.$$

The following result characterizes the solution to $\mathcal{P}^*(z)$.[9]

[7] Extensions of the base model with more general cost structures are discussed in §3.

[8] As an illustration, suppose that the firm incurs setup costs for every production run. If these costs are sufficiently high (relative to the firm's cost of capital r), the firm wants to produce only in the first period, in which case $\tau = 1$, $\hat{\tau} = T$, and $\bar{q}_t = 0$ for all $t > 1$.

[9] Lemma 1 summarizes the solution to the following Langrangean:

$$\max_{\{q_t, s_t\}_t} \sum_{t=1}^{T} \left\{ \gamma^{t-1} \left[R_t(s_t \mid z_t) - cq_t - k \sum_{i=1}^{t} (q_i - s_i) \right] + \lambda_t \sum_{i=1}^{t} [q_i - s_i] + \eta_t [\bar{q}_t - q_t] \right\},$$

where $\{\lambda_t, \eta_t\}_t$ are the multipliers for the inventory and capacity constraints, respectively.

Lemma 1. *If $(q^*(z), s^*(z))$ is z-efficient, i.e., it solves Program $\mathcal{P}^*(z)$, then*:

$$R_t'(s_t^*(z_t) \mid z_t) = \begin{cases} c, & t \notin I, \\ d_{\tau t}, & t \in I, \end{cases} \tag{2}$$

$$q_t^*(z) = \begin{cases} s_t^*(z_t), & t \notin (\{\tau\} \cup I), \\ \bar{q}_t, & t \in I, \\ s_\tau^*(z_\tau) + \sum_{i \in I} [s_i^*(z_i) - \bar{q}_i], & t = \tau. \end{cases} \tag{3}$$

For all periods of the inventory cycle, $t \in I$, the relevant marginal cost to be matched with marginal revenues is $d_{\tau t}$, the compounded period-τ production cost plus the accrued (and compounded) holding cost. Note in particular that linearity of the production and holding costs implies that the firm's optimization problem is separable across periods. Denote by $x_{\tau t}$ those units produced in period τ and earmarked for sale in period $t \in I$; then $x_\tau^*(z) = q_\tau^*(z) - s_\tau^*(z) = \sum_{t \in I} x_{\tau t}^*(z_t)$ with $x_{\tau t}^*(z_t) = s_t^*(z_t) - \bar{q}_t$.

3. Goal-Congruent Performance Measures

We now turn to a decentralized setting where operating decisions are delegated to the manager, assuming only the manager knows z. In each period t, the manager is evaluated based on some performance metric, Π_t. For the most part of the paper, we confine attention to cash flow, income, or residual income as the most commonly used metrics. At the beginning of any period t, the manager seeks to maximize

$$\sum_{i=t}^{T} \gamma^{i-t} u_i \Pi_i(\cdot), \tag{4}$$

where u_i is the incentive weight (or bonus coefficient) attached to a dollar of the performance metric in period i. In solving the agency problem in §5, the optimal bonus coefficients will emerge endogenously given the underlying moral-hazard problem. For now, we take the vector $u \equiv (u_1, \ldots, u_T)$ as given and require that the manager have *robust incentives* for implementing the z-efficient production and sales plan. Formally, $(q^*(z), s^*(z))$ must maximize the objective function in (4) for an entire range of possible u.[10]

Initially, suppose that performance measures are based on cash flow only. A commonly cited advantage of accounting information for performance evaluation is the memory embedded in historical cost information. To create the strongest possible case for cash-flow-based performance measures, we thus consider metrics based on the entire *history* of cash flows:

$$CF_t^h \equiv \sum_{i=1}^{t} \beta_{ti} CF_i, \tag{5}$$

where $\{\beta_{ti}\}_{t,i}$ are design variables chosen by the principal. If $\beta_{ti} = 0$ for all $i < t$ and $\beta_{tt} = 1$ for all t, this performance measure reduces to current cash flow. Alternatively, the coefficients β_{ti} can be chosen so as to allow for complete "backloading" of the performance measure, such that $CF_t^h = 0$ for all $t < T$, while CF_T^h captures the compounded value of all cash flows over the life cycle. We refer to the class of metrics in (5) as cash-flow-based performance measures.

Proposition 1. *There does not exist a cash-flow-based performance measure that creates robust incentives for implementing the z-efficient production and sales plan.*

Proof. All proofs are in the appendix.

To illustrate this result, consider a product with a two-period life cycle ($T = 2$) and constrained capacity in period 2. Then, x_1 affects CF_1^h via production and holding costs $(c+k)x_1$, and it affects CF_2^h via revenues, $R_2(\cdot \mid z_2)$, and historical costs, $\beta_{21}(c+k)x_1$. By our definition of robust incentive provision, u_1 and u_2, which determine how the manager trades CF_1^h for CF_2^h, can take on a range of values. For instance, if $u_1 = u_2$, then it must be that $\beta_{21} = 0$ for the manager to internalize the principal's objective. If $u_1 > u_2$, the manager would underproduce for $\beta_{21} = 0$ because he would value future revenues less than does the principal. To correct for this bias, the principal would need to set $\beta_{21} < 0$, effectively granting the manager a partial refund in period 2 for costs incurred in period 1. The reverse would have to hold for $u_1 < u_2$. Because β_{21} has to be chosen independently of u, however, the manager's intertemporal preferences will generally not be aligned with those of the owner.

Cash-flow-based performance evaluation therefore fails from an incentive perspective, not for lack of memory, but for lack of intertemporal matching.[11] Information about value creation is lost as production costs incurred for concurrent sales are lumped together with costs of future sales. Thus, units produced today for future sale affect the performance metric of more than one period, making it impossible to achieve goal congruence for a range of incentive weights u.

[10] The vector u can vary freely in an open neighborhood around some reference point $u^o \equiv (u_1^o, \ldots, u_T^o)$. Similarly, the vector z is drawn from some open neighborhood in $\Re^T$.

[11] Dutta and Reichelstein (1999) demonstrate that cash-flow-based performance measures may be defective as they expose a risk-averse manager to random fluctuations beyond his control. In contrast, an accrual accounting system can incorporate information beyond the actual cash flows so as to shield the manager from extraneous risk.

We now introduce accrual accounting and argue that the resulting performance metrics lead to better intertemporal separation. In particular, finished-goods inventory is recorded as an asset and expensed only when the respective units are sold. Let V_t denote the inventory value at the end of period t. Of particular interest is the *historical cost* rule: Production costs are capitalized for units in ending inventory and holding costs are expensed as incurred; thus, $V_t = cx_t$ (with $V_0 = 0$). Income under historical cost accounting then equals revenues less cost of goods sold (COGS) and inventory holding costs:

$$\mathrm{Inc}_t = CF_t(q_t, s_t \mid z_t) + V_t - V_{t-1} = R_t(s_t \mid z_t) - cs_t - kx_t, \quad t \in I.$$

Despite its ubiquitousness, accounting income is readily seen to bias managerial incentives in connection with inventory decisions: If $u_i = u_j$ for any $i, j \in I$ (constant bonus coefficients over time), the manager will have an incentive to produce (and sell) excessive quantities because income fails to account for the time value of money.

As a modification to income, residual income (RI_t) is being used increasingly for performance measurement purposes. Residual income imposes an additional capital charge, calculated according to the firm's cost of capital, on the value of operating assets (here, inventory) at the beginning of the period:

$$RI_t = \mathrm{Inc}_t - rV_{t-1} = CF_t(q_t, s_t \mid z_t) + V_t - (1+r)V_{t-1}.$$

The following simple example illustrates the incentive properties of residual income based on historical cost.

Example. The product has a three-period life and inventory cycle ($\tau = 1$ and $\hat{\tau} = T = 3$), with production occurring only in period 1 ($\bar{q}_2 = \bar{q}_3 = 0$) and zero holding costs ($k = 0$). For any $z = (z_1, z_2, z_3)$, the manager chooses

$$\max_s \{u_1[R_1(s_1 \mid z_1) - cs_1] + \gamma u_2[R_2(s_2 \mid z_2) - cs_2 - rc(s_2 + s_3)] + \gamma^2 u_3[R_3(s_3 \mid z_3) - (1+r)cs_3]\},$$

and $q_1 = \sum_t s_t$. It is straightforward to see that the manager will indeed select the optimal sales quantities for the first two periods. However, the necessary first-order condition for his optimal choice of s_3 is

$$R_3'(s_3 \mid z_3) = (1+r)\left(1 + r\frac{u_2}{u_3}\right)c.$$

A comparison with (2) reveals a bias in the manager's decision making: He will sell the desired quantity $s_3^*(z_3)$ only if $u_2 = u_3$.[12] This dependence on the incentive weights arises because s_3 affects both RI_2 and RI_3. As argued above, however, these weights can assume a range of values. Residual income thus does not create robust incentives to implement the z-efficient quantity plan when inventory is valued at (nominal) historical cost.

Now consider a modified valuation rule that treats inventory as an interest-accruing asset in that the value of each unit that remains in ending inventory in a given period increases at the interest rate r. That is, $V_t = \gamma^{-(t-1)} cx_t$, and hence (recall that $k = \bar{q}_2 = \bar{q}_3 = 0$ and $\tau = 1$ in this example):

$$RI_t = R_t(s_t \mid z_t) - (1+r)^{t-1} cs_t.$$

At any date t, the ending inventory appreciates at the interest rate. At the same time, residual income imposes a capital charge on the x_{t-1} units in beginning inventory. These two effects cancel each other precisely for the remaining x_t units in ending inventory. The effective cost-of-goods-sold charge becomes $(1+r)^{t-1} cs_t$, which, by comparison with the z-efficient solution in (2), makes residual income proportional to the firm's objective in each period.

The preceding example suggests a *compounded historical cost valuation rule* that capitalizes production costs and periodic holding costs incurred and in addition treats inventory as an interest-accruing asset. As production occurs over multiple periods, the firm needs to specify an inventory flow rule, e.g., LIFO or FIFO. With inventory treated as interest accruing, units taken from more recent inventory layers carry a lower value than those from earlier layers, despite our assumption of nominally constant production costs over time, c. For instance, if $q_t = s_t$ for some period t, the compounded historical cost rule combined with the LIFO rule yields an ending inventory value of $V_t = (1+r)V_{t-1} + kx_t$.

The following result focuses on a setting in which all periods of the inventory cycle are "net importers" of quantities produced in period τ.

Assumption 1. *$s_t^*(z_t) > \bar{q}_t$ for all z and for all $t \in I$.*

Assumption 1 implies that the optimal stock of units in inventory is monotonically decreasing over time; i.e., $x_t^*(z) \geq x_{t+1}^*(z)$ for all $t \in I$.

Proposition 2. *Given Assumption 1, residual income based on compounded historical cost valuation and the LIFO rule creates robust incentives for implementing the z-efficient production and sales plan.*

If all periods $t \in I$ are net importers of units produced in period τ, then under the LIFO rule the q_t units produced in t are expensed first, at a per-unit value of c. The remaining $(s_t - q_t)$ units sold are valued at $d_{\tau t}$ each. Compounded historical cost accounting with LIFO costing therefore succeeds under the

[12] By the "conservation property" of residual income (Preinreich 1937), the present value of residual income always equals the net present value, provided the capital charge rate equals the firm's discount rate. Hence, if $u_i = u_j$ for all i, j, the manager will seek to maximize the present value of future cash flows.

conditions of Assumption 1 because the resulting cost charge for the last (marginal) unit sold, $d_{\tau t}$, always equals the shadow price of a unit of capacity in period t. To further illustrate this point, suppose that the manager produces $q_t^*(z) = \bar{q}_t$ for all $t \in I$. Then, for all sales quantities $s_t \geq \bar{q}_t$ throughout the inventory cycle, this valuation method yields

$$V_t = \gamma^{-(t-\tau)} c x_t + \sum_{i=0}^{t-\tau} (1+r)^i k x_t = (d_{\tau t} + k) x_t, \quad (6)$$

$$RI_t = R_t(s_t \mid z_t) - d_{\tau t} s_t + (d_{\tau t} - c) q_t. \quad (7)$$

Note that residual income in period t is affected only by that period's production and sales quantities, rendering the performance metrics separable across periods. The last term in (7), $(d_{\tau t} - c) q_t > 0$, provides the manager with incentives to produce at capacity for all $t \in I$, which conforms with the z-efficient production and sales plan. A comparison of (7) and (2) shows that the manager internalizes the principal's objective.[13]

The compounded historical cost rule is generally not used for external financial reporting purposes. While GAAP treats certain financial assets and liabilities as interest bearing, real assets are generally not adjusted for interest gains or charges. Similar discrepancies with GAAP have emerged in the more recent literature on accounting adjustments for so-called economic profit plans such as EVA (e.g., Young and O'Byrne 2001, Ehrbar 1998). This literature has generally concluded that matching of revenues and expenses is central to periodic performance measurement, but that GAAP generally fails to account properly for the time value of money.[14] Ehrbar (1998) advocates the concept of "strategic investments," referring to a wide class of real and financial assets that should be treated as interest bearing for the purpose of internal performance measurement. Ehrbar's reasoning is essentially the one articulated in connection with Proposition 2 above: Until such time as an asset generates cash flows, it should not affect the residual income measure. This requires the accrual of interest gains that are then precisely offset by the capital charge on assets.

It is straightforward to construct examples showing that, in contrast to LIFO, the FIFO rule cannot align the preferences of managers and owners. To illustrate, let $t^o \in I$ denote the period in which the initial inventory layer, x_τ, is fully depleted under FIFO. The cost charge for the last unit sold in subsequent periods—say, period $t^o + 1$—then differs from $d_{\tau,\, t^o+1}$. Moreover, s_{t^o+1} then affects not only RI_{t^o+1}, but also RI_{t^o}. As a consequence, the performance measures are no longer separable across time and the manager's decisions will depend on the weights u_t that he attaches to different periods.

Proposition 3. *Suppose that Assumption* 1 *holds and there exists some period* $t^o \in \{\tau+1, \dots, \hat{\tau}-1\}$ *such that* $x_\tau^*(z) < \sum_{i=\tau+1}^{t^o} [s_i^*(z_i) - \bar{q}_i]$ *for some z. Then, residual income based on compounded historical cost valuation and the FIFO rule fails to create robust incentives for implementing the z-efficient production and sales plan.*

When Assumption 1 is not met, the LIFO method, too, will generally fail from an incentive perspective for reasons similar to those mentioned above: If some periods $t \in I$ are "net contributors" to inventory ($s_t^*(z_t) < \bar{q}_t$), then residual income under the LIFO rule will no longer be intertemporally separable and the cost charge for units sold in some periods will differ from $d_{\tau t}$. However, a modified historical cost-based valuation method can still generate the desired incentives. In particular, suppose that ending inventory is valued at $V_t = (d_{\tau t} + k) x_t$. We refer to this as *compounded period-τ cost valuation*. This method always results in residual income values as stated in (7).

Corollary to Proposition 2. *Residual income based on compounded period-τ costs creates robust incentives for implementing the z-efficient production and sales plan.*

We note that our finding in Proposition 2 preserves a key feature of historical cost accounting: The cost incurred for an individual output unit is expensed (adjusted for capitalized holding costs and the time value of money) when the unit is sold. This is no longer the case under the compounded period-τ cost method. Here, the last unit sold carries a value of $d_{\tau t}$ irrespective of when it was actually produced, because each output unit is immediately "marked-up" in value from c to $d_{\tau t}$ upon production. This valuation method effectively bypasses the issue of inventory flow altogether and ensures that the manager always internalizes the relevant marginal cost charge, even in periods in which inventory is replenished (i.e., Assumption 1 fails). While this is a clear departure from GAAP, the additional degree of freedom seems crucial for generating the desired incentives in environments more general than the ones postulated in Proposition 2.

To conclude this section, we revisit several assumptions that have simplified the preceding analysis. Specifically, unit costs were assumed to be constant and time invariant, and production did not require

[13] We implicitly assume that, given Assumption 1, the manager is required under the LIFO rule always to sell at least as many units as produced in periods with strictly positive beginning inventory. An immediate consequence of the z-efficient solution in Lemma 1 is that it is never optimal to set $q_t > s_t$ for any period in which $x_{t-1}^*(z) > 0$. Note that our assumption that the principal knows the beginning and ending dates of the inventory cycle I is not essential for implementing the LIFO rule.

[14] Paton and Stevenson (1918) express caution with regard to the capitalization of interest because it makes the accounting rules contingent on the firm's rate of return, which may by subject to ambiguity.

any fixed costs. On the last point, relevant fixed costs may arise if the manager can make upfront investments (e.g., PP&E, personnel training, R&D) that lower the subsequent unit variable production cost. It is straightforward to see that a system of *full absorption costing* will generally not align incentives in such settings.[15] In contrast, a system of *variable costing* can induce goal congruence if COGS is computed based only on (compounded) variable cost. However, the residual income measure must also include depreciation and capital charges for the initial investment. To ensure proper incentives for the manager to make the optimal inventory depletion decisions, the depreciation schedule for the investment should reflect the *expected* (rather than actual) future sales quantities.

Propositions 2 and 3 can be easily be generalized so as to allow for the possibility of time-dependent variable costs $\{c_t\}_{t=1}^T$.[16] In contrast, it would be difficult to accommodate general (nonlinear) cost functions, $\{C_t(q_t)\}_{t=1}^T$. The z-efficient production and sales plan given in Lemma 1 would then no longer be intertemporally separable. In order for the marginal cost charge to equal the relevant cost, inventory would need to be carried at the compounded marginal period-τ cost evaluated at q_τ: $\bar{d}_{\tau t} \equiv (1+r)^{t-\tau} C'_\tau(s_\tau + \sum_{i\in I} x_{\tau i})$ (ignoring holding cost). As $\bar{d}_{\tau t}$ depends on all $x_{\tau i}$, $i \in I$, the manager's optimal choice will vary with the weights u_t. Thus, cost-based inventory valuation rules will no longer generate robust incentives when the periodic cost functions are nonlinear.[17]

4. Additional Forecast Information

Our analysis so far has focused on a deterministic setting where the manager had perfect foresight regarding all future revenue functions at the outset. In many situations of interest, however, updated information about future revenues becomes available after the initial production decision has been made. Such dynamic environments render the delegation problem more demanding: In addition to building up the optimal amount of inventory, the manager should also have incentives to update the optimal inventory depletion policy in subsequent periods once this new forecast information becomes known. To simplify the exposition in this section, we normalize the inventory cycle so that $\tau = 1$.

Consider first the case of a "short-lived" product with $T = \hat{\tau} = 2$. To incorporate the notion of additional forecast information, suppose that the manager observes the realization of another random variable, μ, at the beginning of the second period, where μ affects period-2 revenues. The distribution of μ is commonly known at the outset with $E_\mu[\cdot]$ as the corresponding expectation operator. With $p_2(\mu)$ denoting the salvage price in period 2, the maximum achievable revenue in that period is equal to

$$\hat{R}_2(s_2 \mid z_2, \mu) \equiv \max_{s_2^o \in [0,\, s_2]} \{R_2(s_2^o \mid z_2, \mu) + p_2(\mu)[s_2 - s_2^o]\}, \tag{8}$$

with $s_2 \in F_2(x_1)$ according to (1). Cash flow in period 2 is

$$CF_2(q_2, s_2 \mid z_2, \mu) = \hat{R}_2(s_2 \mid z_2, \mu) - cq_2, \tag{9}$$

provided $x_2 = 0$. We assume that $0 < \gamma p_2(\mu) \le c + k$ for all μ; hence, the firm would not produce any units to sell them at the salvage price if it knew μ at the outset. However, the inventory buildup decision has to be made in expectation over all μ. For some realizations of μ, $R_2(\cdot \mid z_2, \mu)$ may be so unattractive that the firm finds it advantageous ex post to sell some units at $p_2(\mu)$. Note that sunk cost considerations imply that all units should be sold at the end of period 2, either in the regular market or at the salvage price.

As a benchmark, first consider the optimal policy from the principal's perspective. Applying backward induction, the conditionally optimal period-2 production quantity for any (x_1, z_2, μ) is given by

$$q_2^*(x_1 \mid z_2, \mu) \in \arg\max_{q_2 \le \bar{q}_2} CF_2(q_2, s_2^*(x_1 \mid z_2, \mu) \mid z_2, \mu), \tag{10}$$

where $s_2^*(\cdot) \equiv x_1 + q_2^*(\cdot)$. Now consider the first period: By (2), the optimal sales quantity is given by $R_1'(s_1^*(z_1) \mid z_1) = c$, while

$$x_1^*(z_2) \in \arg\max_{x_1} \{\gamma E_\mu[CF_2(q_2^*(x_1 \mid z_2, \mu), s_2^*(x_1 \mid z_2, \mu) \mid z_2, \mu)] - (c+k)x_1\}. \tag{11}$$

It is readily seen that the solution identified in Proposition 2—residual income based on compounded historical cost—does not generate proper incentives for the manager to sell off all units at the end of period 2 in case of an unfavorable realization of μ. Suppose that μ is such that some units should be sold at the salvage price $p_2(\mu)$. Every such unit, however, reduces residual income in period 2 by $[(1+r)(c+k) - p_2(\mu)] > 0$, thus making it impossible to generate robust incentives.

Financial accounting rules for inventory valuation usually require the lower-of-cost-or-market rule when market prices are available. In our setting with $T = 2$, this method prescribes inventory values of

[15] A common illustration of misaligned incentives under absorption costing is that "impatient" managers tend to overproduce and build up excessive inventories. This would defer the expensing of fixed costs to later periods.

[16] Implicitly, we impose the mild regularity condition that $\gamma c_{t+1} \le c_t$ for all t. Otherwise, the firm would hold inventory even with unconstrained capacity.

[17] While it is likely that actual production costs are nonlinear, most cost-accounting systems presume a linear cost structure.

$V_1 = (c+k)x_1$ and $V_2 = p_2(\mu)$. The corresponding residual income values are

$$RI_1 = R_1(s_1 \mid z_1) - cs_1,$$
$$RI_2 = R_2(s_2^o \mid z_2, \mu) + p_2(\mu)[s_2 - s_2^o] - cq_2 - (1+r)(c+k)x_1. \quad (12)$$

We then obtain the following result:

Proposition 4. *Suppose that the product has a two-period life cycle* ($T = 2$) *and the manager learns additional forecast information*, μ, *at the end of period* 1. *Then, residual income based on the lower-of-cost-or-market rule creates robust incentives for implementing the z-efficient production and sales plan.*

The lower-of-cost-or-market rule thus successfully straddles two objectives. In period 1, the manager internalizes the relevant cost of building up inventory. In period 2, he correctly views the historical cost as sunk because any ending inventory is written off to the prevailing salvage price. There is a longstanding debate in the accounting literature on the use of historical cost versus market information.[18] Our stewardship perspective suggests that historical cost valuation is appropriate for inventory provided the manager can accurately forecast future revenues. The lower-of-cost-or-market rule, on the other hand, works well if market conditions are uncertain and the product has a short life cycle.[19]

The natural question at this point is whether asset valuation rules can be found that robustly implement z-efficient quantities if the manager learns additional forecast information and the life cycle exceeds two periods ($T > 2$). At the end of period 1, the manager again observes the realization of μ, but μ now affects all future revenue functions and salvage prices, $\{R_t(s_t \mid z_t, \mu), p_t(\mu)\}_{t=2}^T$. In our search for goal-congruent performance measures, we confine attention to linear combinations of current accounting information—cash revenues and costs, as well as current and lagged asset values:[20]

$$\Pi_t = \alpha_1 R_t(s_t \mid z_t, \mu) + \alpha_2 c q_t + \alpha_3 k x_t + \alpha_4 V_t(\cdot) + \alpha_5 V_{t-1}(\cdot). \quad (13)$$

We allow for the inventory valuation rule, $\{V_t(\cdot)\}_t$, to depend on past and current production costs, revenues, and salvage prices. Additional details are provided in the proof of Proposition 5 in the appendix.

Proposition 5. *Suppose that* $T > 2$ *and the manager learns additional forecast information*, μ, *at the end of period* 1. *Then, there does not exist a performance measure of the form in* (13) *that creates robust incentives for implementing the z-efficient production and sales plan.*

When the random variable μ is degenerate and concentrates its entire mass on one point, the setting considered in Proposition 5 coincides with that in Proposition 2. For the simple case where production occurs only in period 1 (possibly due to high setup costs) so that Assumption 1 holds, we demonstrate in the appendix that residual income based on compounded period-1 costs is essentially the *unique* method for generating robust incentives within the linear class in (13).[21] On the other hand, this performance measure will generally introduce a bias into the inventory-depletion decisions once the random shock μ can assume a range of values, because the manager's decision problem will no longer be intertemporally separable.

5. Optimal Incentive Schemes

This section introduces an explicit agency problem into the model. In each period t, the manager now chooses the sales productivity parameters z_t in addition to the quantities q_t and s_t. The choice of z_t is assumed to impose a personal cost on the manager. The magnitude of this cost depends on an underlying state variable θ known only to the manager. We demonstrate that the principal can achieve an optimal (second-best) contracting arrangement by basing compensation payments on the performance measure and inventory valuation rules identified in Propositions 2 and 4.

As is common in adverse selection models, the manager is assumed to observe his private information, θ, prior to contracting.[22] It will be notationally convenient to suppress the effort variable and instead to denote the manager's unobservable disutility (cost) of effort by the multiplicatively separable function

[18] See, e.g., Paton and Stevenson (1918), Edwards and Bell (1961), Chambers (1966), and Ijiri (1967).

[19] In the context of disclosure, rather than management control, Reis and Stocken (2002) consider the differential information content of historical cost-based and market-based asset valuation rules as they relate to capacity decisions made by oligopolistic competitors.

[20] Given clean surplus accounting, i.e., income is equal to cash flow plus the change in book value, COGS is uniquely determined by the variables included in Π_t. Hence, there is no loss of generality in excluding COGS from (13).

[21] This necessity result for historical cost accounting (for the case of $T > 2$ and perfect foresight on the part of the manager) contrasts with Dutta and Zhang (2002), who show optimality of historical cost accounting if sales decisions are exogenously given. However, because their model is confined to two periods, the lower-of-cost-or-market rule is optimal in this case as well. Hence, there is no need for the firm to employ historical cost accounting in their model.

[22] Equivalently, the manager may receive his private information after contracting, but he cannot be prevented from quitting at any time.

$D_t(z_t \mid \theta) = z_t h_t(\theta)$, with $h_t(\cdot)$ increasing and convex in θ. The principal's prior beliefs regarding θ are given by the density function $f(\theta)$ with cumulative distribution function $F(\theta)$ on the interval $\Theta = [\underline{\theta}, \bar{\theta}]$. We adopt the following variant of the monotone hazard rate condition commonly used in adverse selection models (e.g., Laffont and Tirole 1993):

Assumption 2. *The function*

$$\left[\frac{h_t'(\theta)}{h_t(\theta)} \frac{F(\theta)}{f(\theta)}\right]$$

is increasing in θ for all t.

In a setting without additional forecast information (i.e., μ is absent), the principal devises a mechanism specifying the choices $\{y_t(\tilde{\theta}), z_t(\tilde{\theta}), q_t(\tilde{\theta}), s_t(\tilde{\theta})\}_{t=1}^T$ in response to the manager's report $\tilde{\theta}$, where $y_t(\tilde{\theta})$ denotes the manager's compensation in period t. We note that there is no loss of generality in assuming that the parameters z_t are contractible provided the principal observes the sales quantities and the actual sales revenues. If the manager were to report $\tilde{\theta}$ while actually being of type θ, his utility payoff would be

$$U(\tilde{\theta}, \theta) = \sum_{t=1}^{T} \gamma^{t-1}\big[y_t(\tilde{\theta}) - z_t(\tilde{\theta}) h_t(\theta)\big].$$

Without loss of generality, the manager's reservation utility is normalized to zero. By the Revelation Principle, the principal commits to a direct revelation mechanism so as to maximize future discounted cash flows net of managerial compensation:

$$\mathcal{P}^z: \max_{\{z_t(\theta), y_t(\theta), q_t(\theta), s_t(\theta)\}_{t=1}^T} \int_{\underline{\theta}}^{\bar{\theta}} \sum_{i=1}^{T} \gamma^{i-1}\big[CF_i(q_i(\theta), s_i(\theta) \mid z_i(\theta)) - y_i(\theta)\big] f(\theta)\, d\theta,$$

subject to, for all t, θ, and $\tilde{\theta}$:

$$(s_t(\theta), q_t(\theta)) \in F_t(x_{t-1}(\theta)),$$

$$U(\theta, \theta) \geq 0,$$

$$U(\theta, \theta) \geq U(\tilde{\theta}, \theta).$$

The three constraints ensure, respectively, feasibility of the quantity choices, individual rationality, and incentive compatibility. We denote the solution to Program $\mathcal{P}^z$ by $\{z_t^*(\theta), y_t^*(\theta), q_t^*(\theta), s_t^*(\theta)\}_{t=1}^T$, and refer to it as the *second-best solution*.

The fundamental trade-off for the principal in this contracting problem is that higher productivity parameters, $z_t(\theta)$, can be achieved only at the expense of larger informational rents for the manager, that is, compensation payments exceeding the cost of effort. Because each z_t affects current revenues, $R_t(s_t \mid z_t)$, both $x_{\tau t}(\cdot)$ and $q_t(\cdot)$ depend only on z_t (and not on z_τ) for $t \in I$. This intertemporal separability allows us to define the following benefit functions:

$$B_t(z_t) \equiv \begin{cases} \max_{s_t} \{B_t(s_t \mid z_t) \equiv R_t(s_t \mid z_t) - c s_t\}, & t \notin I, \\ \max_{(q_t, x_{\tau t})} \{B_t^I(q_t, x_{\tau t} \mid z_t) \equiv R_t(x_{\tau t} + q_t \mid z_t) \\ \qquad - c q_t - d_{\tau t} x_{\tau t}\}, & t \in I, \end{cases} \tag{14}$$

subject to the feasibility constraints in (1). Standard techniques for solving adverse selection problems then yield the following result.

Lemma 2. *Given Assumption 2, the second-best solution to the principal's problem $\mathcal{P}^z$ is found by choosing $\{z_t^*(\theta)\}_{t=1}^T$ according to*

$$z_t^*(\theta) \in \arg\max_{z_t} \{B_t(z_t) - z_t H_t(\theta)\}, \tag{15}$$

where $H_t(\theta) \equiv h_t(\theta) + h_t'(\theta)(F(\theta)/f(\theta))$.

The principal implements the second-best sales productivity parameters so as to maximize (pointwise and in present value terms) the difference between the achievable contribution margin and the manager's virtual cost of effort, $z_t H_t(\theta)$.[23] The optimal quantity choices $\{q_t^*(\theta), s_t^*(\theta)\}_{t=1}^T$ are the maximizers of the benefit functions in (14) evaluated at $z_t = z_t^*(\theta)$ for all t. Put differently, the second-best production and sales plan consists of the quantities according to (2)–(3) conditional on the second-best sales productivity parameters. It can be shown that the manager's informational rent is equal to

$$U(\theta, \theta) = \int_{\theta}^{\bar{\theta}} \sum_{i=1}^{T} \gamma^{i-1} z_i^*(\xi) h_i'(\xi)\, d\xi. \tag{16}$$

We now demonstrate that the preceding benchmark solution can be implemented by a delegation scheme where the manager makes all operating decisions; that is, in each period he chooses (z_t, q_t, s_t). At the outset, the principal offers the manager a menu of linear compensation schemes based on Π_t:

$$\big\{y_t(\tilde{\theta}, \Pi_t) = w_t(\tilde{\theta}) + u_t(\tilde{\theta}) \cdot \Pi_t\big\}_{t=1}^T. \tag{17}$$

By reporting $\tilde{\theta}$, the manager selects T contracts—one for each period—from this menu. A performance measure $\{\Pi_i\}_{i=1}^T$ is said to be *optimal* if there exists a menu of linear contracts $\{w_t(\tilde{\theta}), u_t(\tilde{\theta})\}_{t=1}^T$ based on $\{\Pi_i\}_{i=1}^T$, which implements the second-best solution.

Note that the above delegation scheme specifies far fewer policy variables than the centralized revelation mechanism.[24] In particular, only the contract

[23] This virtual cost comprises the actual cost $z_t h_t(\theta)$ and the expected informational rent.

[24] While delegation schemes appear to be easier to implement than revelation mechanisms, our present framework does not capture

parameters $\{w_t(\tilde{\theta}), u_t(\tilde{\theta})\}_t$ depend on the agent's message $\tilde{\theta}$, whereas the performance measures, $\{\Pi_t\}_t$, are independent of $\tilde{\theta}$. We also note that all memory requirements of the long-term contract are embodied in the performance measure via the accrual accounting rules.

Proposition 2′. *Given Assumptions* 1 *and* 2, *residual income based on compounded historical cost and the LIFO rule is an optimal performance measure.*

It follows directly from Proposition 2 that, upon selecting the optimal $z_t^*(\theta)$, the manager will also choose the second-best production and sales quantities. If the bonus coefficients are set equal to

$$u_t(\tilde{\theta}) = \frac{h_t(\tilde{\theta})}{H_t(\tilde{\theta})} \tag{18}$$

for any t, then the manager will equate marginal benefits, $B_t'(z_t)$, with the marginal virtual costs of choosing the sales productivity parameters in (15). Following a truthful report of θ, it is therefore in the manager's best interest to choose $\{z_t^*(\theta)\}_t$.[25] Note that $0 \leq u_t(\theta) \leq 1$, so that $u_t(\theta)$ can indeed be interpreted as a bonus coefficient. Finally, the fixed salary payments, $w_t(\tilde{\theta})$, can be chosen so that the manager's informational rent in period t becomes $\int_\theta^{\bar{\theta}} z_t^*(\xi) h_t'(\xi)\, d\xi$, which, when discounted and summed over all periods, coincides with the expression in (16). Because the participation constraints are satisfied (with slack) in each period, commitment to a long-term contract by the manager is not essential.[26]

At first glance it may seem surprising that the performance measures derived in the goal congruence framework of §3 can also be part of an optimal agency solution. The general theme in private information contracting models is that the optimal second-best mechanism entails distortions in the resource allocations to economize on the informational rents earned by the agent. We find that the optimal productivity parameters, z_t^*, will be curtailed (the principal imputes the agent's virtual rather than true cost). While by implication the optimal production sales quantities will also be distorted downward relative to the first-best, they remain given by the z-efficient production and sales plan (now conditional on $\{z_t^*(\theta)\}_t$) because the agent does not earn any additional rents in connection with these choice variables.[27]

Recent principal-agent studies by Christensen et al. (2002), Dutta and Reichelstein (2002), and Baldenius (2003) have shown that for residual income to be an optimal performance measure, the capital charge rate should be increased beyond the firm's actual cost of capital, r. This result stands in contrast to our finding in Proposition 2′. Essential to our result is that cash flows are a function of "resources committed" and the contractible productivity parameters, z_t. In contrast, the above studies presume that cash flows are a joint (and nonseparable) function of resources committed, managerial effort, and the state of the world. To economize on the agent's informational rent, the principal then finds it advantageous to curtail the amount of resources committed. In a delegation scheme, this is accomplished by a higher capital charge rate.

To conclude this section, consider again the setting in §4: The product has a two-period life cycle and the manager obtains additional information, μ, at the end of period 1. Proposition 4 can also be extended to include a formal agency problem similar to that in Proposition 2′. Specifically, if the manager privately observes θ and μ and exerts personally costly effort in both periods (and Assumption 2 holds), then the principal can achieve second-best outcomes by compensating the manager based on residual income and employing the lower-of-cost-or-market rule. The appropriate menu of incentive contracts $\{y_t(\tilde{\theta}, \Pi_t) = w_t(\tilde{\theta}) + u_t(\tilde{\theta}) \cdot \Pi_t\}_{t=1}^2$ is conditioned upon the manager's initial report $\tilde{\theta}$ but does not require a second report—say $\tilde{\mu}$—to be made once μ is realized.[28] This construction exploits the fact that there is no need to pay the manager additional informational rents due to the new private information variable μ to be observed after the contracting stage, provided he can commit to a two-period contract at the outset.

6. Conclusion

This paper has examined the role of historical cost information in providing managers with incentives for efficient inventory management. We have demonstrated that it is advantageous from a management control perspective to capitalize the production cost

these benefits explicitly. Earlier literature on responsibility centers (e.g., Melumad et al. 1992) has invoked notions of limited communication to obtain an explicit demand for delegated decision making.

[25] To ensure global incentive compatibility of the menu of linear contracts in (17), it is necessary and sufficient that less-efficient types (higher values of θ) receive a smaller bonus coefficient $u_t(\theta)$. This is equivalent to Assumption 2; see Melumad et al. (1992).

[26] In contrast, commitment by the principal is essential for optimality of the incentive scheme. See Baiman and Rajan (1995) and Indjejikian and Nanda (1999) for agency models in which the principal cannot commit to long-term contracts.

[27] Similar observations apply to the studies of Melumad et al. (1992) and Vaysman (1996).

[28] The proofs of Propositions 4 and 2′ can be combined to show the optimality of the lower-of-cost-or-market rule. A technical complication arises from the fact that the optimal second-period productivity parameter $z_2^*(\cdot)$ will depend on θ and μ, with μ unknown at the time the manager reports $\tilde{\theta}$. It is readily seen, though, that $E_\mu[z_2^*(\tilde{\theta}, \mu)]$ is indeed monotone in $\tilde{\theta}$, which is sufficient for global incentive compatibility.

of finished-goods inventory and to recognize these costs in income only at the date of sale. If inventory is treated as an interest-bearing asset, the residual income performance measure will reflect the value created by the production and sales decisions in the period of sale. Until that date, the residual income performance measure is unaffected by the manager's decision to build up inventory.

We have also identified a role for the lower-of-cost-or-market rule for short-lived products that are sold in market environments characterized by uncertainty beyond the manager's initial information. In such environments, however, accounting and market-based performance measures will generally fail to align incentives for products with longer life cycles. The reason is that sunk cost considerations will then collide irreconcilably with opportunity cost considerations.

There are several promising avenues for extending the results of this paper. First, while we established the impossibility of achieving robust goal congruence in environments with sequential information arrival and longer life cycles, it would be desirable to characterize optimal second-best mechanisms for such environments. Second, as pointed out in §5, our agency results have relied substantially on a form of separability between the moral-hazard and the resource allocation problem. In that sense, our results establish a useful benchmark. Without such separability assumptions, one would expect further distortions in the accounting-based performance measure to implement second-best incentive mechanisms. Recent developments in the theory of dynamic agency seem well suited to address these issues.

Acknowledgments
For helpful comments the authors thank Sunil Dutta, Jonathan Glover, Bjorn Jorgensen, Mike Kirschenheiter, Volker Laux, William Lovejoy (the department editor), Nahum Melumad, Suresh Radhakrishnan, Ulf Schiller, an associate editor, two reviewers, and workshop participants at Columbia University, University of Magdeburg, the EIASM (European Institute for Advanced Studies in Management) Workshop on Accounting and Economics, and the HKUST (Hong Kong University of Science and Technology) Summer Symposium on Accounting Research.

Appendix. Proofs

Proof of Proposition 1. It is sufficient to prove this result for the special case of $T=2$ with $q_2^*(z_2)=\bar{q}_2$ for all z_2 (i.e., $\tau=1$ and $T=\hat{\tau}=2$). We normalize $\beta_{ii}=1$ for all i, without loss of generality. When compensated based on the history of cash flows, the manager seeks to maximize

$$\begin{aligned} &u_1 CF_1(q_1, s_1 \mid z_1) + \gamma u_2[CF_2(q_2, s_2 \mid z_2) + \beta_{21} CF_1(q_1, s_1 \mid z_1)] \\ &\quad = u_1[R_1(s_1 \mid z_1) - c(s_1+x_1) - kx_1] + \gamma u_2\{R_2(x_1+q_2 \mid z_2) \\ &\qquad - cq_2 + \beta_{21}[R_1(s_1 \mid z_1) - c(s_1+x_1) - kx_1]\}, \end{aligned} \tag{A1}$$

subject to $s_1+x_1 \le \bar{q}_1$ and $q_2 \le \bar{q}_2$, using the fact that he will always set $s_2 \equiv x_1+q_2$. Because $q_2^*(z_2)=\bar{q}_2$ for all z_2, Lemma 1 implies that $x_1^*(z_2)$ is given by the first-order condition

$$R_2'(\bar{q}_2 + x_1^*(z_2) \mid z_2) = (1+r)(c+k). \tag{A2}$$

Suppose that the manager indeed plans to produce $q_2 = q_2^*(z_2) \equiv \bar{q}_2$. Then, his choice of x_1 is found by setting the derivative of (A1) with respect to x_1 equal to zero:

$$R_2'(\bar{q}_2 + x_1 \mid z_2) = \left[(1+r)\frac{u_1}{u_2} + \beta_{21}\right](c+k).$$

Direct comparison with (A2) shows that the manager will choose $x_1 = x_1^*(z_2)$ only if $\beta_{21} = (1+r)(1-u_1/u_2)$. By assumption, however, (u_1, u_2) can vary freely over some range while β_{21} is a constant, which proves Proposition 1. □

Proof of Proposition 2. By Assumption 1, LIFO costing results in inventory values of

$$V_t = \left(\gamma^{-(t-\tau)}c + \sum_{i=0}^{t-\tau}(1+r)^i k\right)x_t = (d_{\tau t}+k)x_t$$

if the inventory buildup began in period τ. The additional requirement embedded in LIFO that $s_t \ge q_t$ whenever $x_{t-1}>0$ (see Footnote 13) ensures the units in ending inventory are always those of the layer produced in period τ. Clearly, the manager has no incentives to build up inventory in periods $1,\ldots,\tau-1$. This yields the following performance measures:

$$RI_t(q_t, s_t \mid z_t) = \begin{cases} R_t(s_t \mid z_t) - cs_t & \text{if } x_{t-1}=0, \\ R_t(s_t \mid z_t) - d_{\tau t}s_t + (d_{\tau t}-c)q_t & \text{if } x_{t-1}>0. \end{cases} \tag{A3}$$

The manager then chooses $\{q_t, s_t\}_{t=1}^T$ so as to maximize the following Langrangean:

$$\sum_{t=1}^{T}\left[\gamma^{t-1}u_t RI_t(q_t, s_t \mid z_t) + \hat{\lambda}_t \sum_{i=1}^{t}[q_i - s_i] + \hat{\eta}_t[\bar{q}_t - q_t]\right], \tag{A4}$$

where $\{\hat{\lambda}_t, \hat{\eta}_t\}_{t=1}^T$ are the multipliers for the sales feasibility and capacity constraints, respectively, in (1).

To show that the manager has incentives to implement the z-efficient quantity plan identified in Lemma 1, consider the following benefit functions:

$$B_t(s_t \mid z_t) \equiv R_t(s_t \mid z_t) - cs_t \quad \text{for } t \notin I,$$
$$B_t^I(q_t, x_{\tau t} \mid z_t) \equiv R_t(x_{\tau t}+q_t \mid z_t) - cq_t - d_{\tau t}x_{\tau t} \quad \text{for } t \in I.$$

The z-efficient quantities $\{s_t^*(z_t)\}_{t\notin I}$ and $\{q_t^*(z_t), x_{\tau t}^*(z_t)\}_{t\in I}$ then maximize the following Lagrangean:

$$\begin{aligned} &\sum_{t\notin I}\gamma^{t-1}B_t(s_t \mid z_t) + \sum_{t\in I}\gamma^{t-1}B_t^I(q_t, x_{\tau t} \mid z_t) \\ &\qquad + \sum_{t=1}^{T}\left(\lambda_t \sum_{i=1}^{t}[q_i - s_i] + \eta_t[\bar{q}_t - q_t]\right). \end{aligned}$$

Substituting (A3) into (A4) and performing a change of variables so that $x_{\tau t} \equiv s_t - q_t$ for $t \in I$, we find that the manager internalizes the objective of maximizing discounted future cash flows. Hence, he will implement the z-efficient quantities, irrespective of the weights u_t. This completes the proof of Proposition 2. □

Proof of Proposition 3. To show that FIFO sequencing fails to implement z-efficient quantities, we consider the special case where $\tau = 1$ and $\hat{\tau} = T = 3$ with both $\bar{q}_2$ and $\bar{q}_3$ strictly positive and (as postulated by Assumption 1) $s_t^*(\theta) > \bar{q}_t$ for $t = 2, 3$. Suppose that the manager chooses $(\bar{q}_2, \bar{q}_3)$; we then address his choice of sales quantities (s_2, s_3) under FIFO costing. We consider values (s_2, s_3) in an open neighborhood around the z-efficient values $(s_2^*(z_2), s_3^*(z_3))$, assuming that $s_2^*(z_2) > x_1^*(z) = s_2^*(z_2) + s_3^*(z_3) - \bar{q}_2 - \bar{q}_3$. Then, $V_1 = (c+k)x_1^*(z)$, $V_2 = (c+k)(s_3 - \bar{q}_3)$, and $V_3 = 0$ (the manager will obviously not keep any ending inventory x_3). After some simple transformations:

$$RI_2 = R_2(s_2 \mid z_2) - (1+r)(c+k)s_2 + [rc + (1+r)k](\bar{q}_2 + \bar{q}_3 - s_3),$$
$$RI_3 = R_3(s_3 \mid z_3) - (1+r)(c+k)s_3 + [rc + (1+r)k]\bar{q}_3.$$

Note that the performance measures are not separable across periods because s_3 affects both RI_2 and RI_3. The manager, who maximizes $\sum_{i=1}^{3} \gamma^{i-1} u_i RI_i$, chooses s_2 optimally, but his choice of s_3 is given by the following necessary first-order condition:

$$R_3'(s_3 \mid z_3) = (1+r)\left(1 + \frac{u_2}{u_3} r\right)c + \left[(1+r) + \frac{u_2}{u_3}(1+r)^2\right]k.$$

A comparison with (2) shows that $s_3 \neq s_3^*(z_3)$ unless $u_2 = u_3$. However, by assumption, (u_1, u_2, u_3) are allowed to vary freely over some range, so we conclude that FIFO costing generally induces quantity distortions. □

Proof of Proposition 4. We show that the performance metric in (12) creates incentives for the manager to implement the quantities in (11) and (10). Proceeding by backward induction, we note that in period 2 the manager will always split the period-2 sales quantity s_2 optimally over regular sales and salvage sales, that is, he will always realize $\hat{R}_2(s_2 \mid z_2, \mu)$ for given s_2, z_2, and μ. Given this observation, the manager's objective in (12) implies that for any (x_1, z_2, μ) the manager chooses $(s_2, q_2) \in F_2(x_1)$ so as to maximize

$$RI_2 = \hat{R}_2(s_2 \mid z_2, \mu) - cq_2 - (1+r)(c+k)x_1.$$

Up to a constant, this expression coincides with the firm's period-2 objective in (9). Thus, the manager will make the conditionally efficient period-2 decisions.

In period 1, the manager seeks to maximize $\{u_1 RI_1 + \gamma u_2 E_\mu[RI_2]\}$ over all (s_1, x_1), where $x_1 = q_1 - s_2$. Because he will make the conditionally optimal quantity decisions in period 2, we can separate his choice of s_1 (which trivially will be z-efficient) from that of x_1, which is chosen so as to maximize

$$\gamma u_2 \{E_\mu[\hat{R}_2(s_2^*(x_1 \mid z_2, \mu) \mid z_2, \mu) - cq_2^*(x_1 \mid z_2, \mu)] - (1+r)(c+k)x_1\}.$$

The term in curly brackets is proportional to the principal's objective in (11), completing the proof of Proposition 4. □

Proof of Proposition 5. It suffices to consider a setting where production occurs only in period 1, i.e., $\bar{q}_t = 0$, $t \geq 2$. Inventory flow assumptions are then immaterial and the search for performance measures that robustly implement z-efficient quantities can be confined to linear combinations of current accounting (and market) information of the form

$$\Pi_t = \alpha_1 R_t(s_t \mid z_t, \mu) + \alpha_2 c q_t + \alpha_3 k x_t + \alpha_4 x_t v_t(\cdot) + \alpha_5 x_{t-1} v_{t-1}(\cdot),$$

with $v_t \equiv V_t / x_t$ as the per-unit inventory value. Without loss of generality, the coefficient assigned to revenues can be normalized so that $\alpha_1 = 1$. We allow for the unit inventory values, $v_t(\cdot)$, to depend on: production costs c; holding costs k; the history of per-unit revenues $\{\bar{R}_i\}_{i=1}^t$ (with $\bar{R}_i \equiv R_i(\cdot)/s_i$); and the history of salvage prices $\{p_i(\mu)\}_{i=2}^t$ in a (almost everywhere) differentiable fashion. The coefficients $\{\alpha_j\}_{j=2}^5$ and the inventory valuation rule $\{v_t(\cdot)\}_t$, on the other hand, are chosen independently of u.

The proof proceeds as follows: Step 1 shows that without additional forecast information and production occurring only in period 1, residual income based on compounded period-1 cost is the *unique* solution within the linear class in (13) that creates robust incentives for the manager to implement the z-efficient production and sales plan. In Step 2, we show that this solution fails to achieve this benchmark in the presence of nontrivial additional forecast information.

Step 1. Suppose, as in §3, that μ is degenerate, i.e., it assumes only one value. For notational convenience, we suppress μ throughout Step 1. Suppose that the revenue functions are quadratic, such that $R_t(s_t \mid z_t) = (z_t - s_t)s_t$. For given u, the manager chooses $(q_1, s_1, \ldots, s_T)$ so as to maximize $\sum_{t=1}^{T} \gamma^{t-1} u_t \Pi_t$, subject to $q_1 \geq \sum_{t=1}^{T} s_t$. The resulting first-order conditions are (with λ denoting the Lagrange multiplier)

$$\sum_{i=1}^{T} \gamma^{i-1} u_i \frac{\partial \Pi_i}{\partial q_1} + \lambda = 0,$$
$$\sum_{i=1}^{T} \gamma^{i-1} u_i \frac{\partial \Pi_i}{\partial s_t} - \lambda = 0,$$

for $t = 1, \ldots, T$. By definition of the performance measures in (13), $\partial \Pi_i / \partial s_t = 0$ for all $t > i$, which can be rewritten as follows:

$$\alpha_4 v_t(\cdot) = -\alpha_3 k - \alpha_5 v_{t-1}(\cdot). \tag{A5}$$

Using $\partial \Pi_i / \partial s_t = 0$ for all $t > i$, we can combine the first-order conditions for any q_1 and s_t:

$$\sum_{i=1}^{t-1} \gamma^{i-1} u_i \frac{\partial \Pi_i}{\partial q_1} + \sum_{i=t}^{T} \gamma^{i-1} u_i \left(\frac{\partial \Pi_i}{\partial q_1} + \frac{\partial \Pi_i}{\partial s_t}\right) = 0,$$

which has to hold for all $u = (u_1, \ldots, u_T)$ on some open set in $\Re^T$. In period 1, that implies

$$\frac{\partial \Pi_1}{\partial q_1} = \alpha_2 c + \alpha_3 k + \alpha_4 v_1(\cdot) = 0,$$
$$\frac{\partial \Pi_1}{\partial s_1} = R_1'(s_1^*(z_1) \mid z_1) - \alpha_3 k - \alpha_4 v_1(\cdot) = 0.$$

Combining these equations with the optimality requirement $R_1'(s_1^*(z_1) \mid z_1) = c$, it follows that $\alpha_2 = -1$ and $v_1(\cdot) = (1/\alpha_4)(c - \alpha_3 k)$. In conjunction with (A5) we obtain

$$\alpha_4 v_2(\cdot) = \alpha_3 \left(1 - \frac{\alpha_5}{\alpha_4}\right)k - \frac{\alpha_5}{\alpha_4} c. \tag{A6}$$

Now consider the period-2 performance measure

$$\frac{\partial \Pi_2}{\partial s_2} = R_2'(s_2^*(z_2) \mid z_2) - \alpha_3 k - \alpha_4 v_2(\cdot) = 0.$$

This equation together with $R_2'(s_2^*(z_2) \mid z_2) = (1+r)(c+k)$ and (A6) yields $\alpha_3 = -1$ and $\alpha_5/\alpha_4 = -(1+r)$. For arbitrary t, we find that

$$v_t(\cdot) = \frac{1}{\alpha_4}\left((1+r)^{t-1}c + \sum_{i=0}^{t-1}(1+r)^i k\right).$$

Normalizing $\alpha_4 = 1$, we have $\alpha_5 = -(1+r)$ and $v_t(\cdot) = d_{1t} + k$, which establishes the necessity (up to a normalizing constant) of residual income based on compounded period-1 cost with capitalized inventory holding costs.

Step 2. Now suppose that $T = 3$, and the random variable μ is nondegenerate and drawn from a nonempty interval on the real line. The realization of this variable only affects period-2 revenues. In particular, $R_2(s_2 \mid z_2, \mu) = (z_2 + \mu - s_2)s_2$, while $(R_1(\cdot), R_3(\cdot))$ remain unaffected by μ.[29] Given $(\mu, z_2, z_3, x_1^*(z))$, the optimal period-2 sales are determined by $R_2'(\cdot) = \gamma R_3'(\cdot) - k$, which in this case yields

$$s_2^*(\cdot) = \frac{1}{2(1+\gamma)}[z_2 + \mu - \gamma z_3 + 2x_1^*(z) + k].$$

Having observed μ, the manager seeks to maximize $\{u_2\Pi_2(\cdot) + \gamma u_3 \Pi_3(\cdot)\}$, subject to $s_2 + s_3 \le x_1^*(z)$ (the latter will again hold as an equality). Optimality requires that this objective function be maximized at $s_2^*(\cdot)$, for any (u_2, u_3) in some open set in $\Re^2$. Hence,

$$\left.\frac{\partial \Pi_2}{\partial s_2}\right|_{s_2 = s_2^*(\cdot)} = R_2'(s_2^*(\cdot) \mid z_2, \mu) + k - v_2(\cdot) = 0 \qquad \text{(A7)}$$

has to hold, where, by Step 1, $\alpha_3 = -1$. Also by Step 1, $v_2(\cdot) = (1+r)(c+k) + k$, which can be used for $R_2'(\cdot)$ in (A7):

$$\frac{\gamma}{1+\gamma}(z_2 + \mu) + \frac{1}{1+\gamma}[\gamma z_3 + 2\gamma x_1^*(z) - k] = (1+r)(c+k).$$

This equation cannot hold for all μ, because the left-hand side of the equation is increasing in μ, while the right-hand side is independent of μ. $\square$

Proof of Proposition 2′. We begin by noting that $s_t^*(\theta) \equiv s_t^*(z_t^*(\theta))$ and $q_t^*(\theta) \equiv q_t^*(z_t^*(\theta))$, i.e., the second-best quantities coincide with the z-efficient production and sales plan conditional on the second-best productivity parameters. Proposition 2 implies that if the manager chooses $z^*(\theta) \equiv (z_1^*(\theta), \ldots, z_T^*(\theta))$, then he also has incentives to implement $s^*(\theta) \equiv (s_1^*(\theta), \ldots, s_T^*(\theta))$ and $q^*(\theta) \equiv (q_1^*(\theta), \ldots, q_T^*(\theta))$. Thus, it remains to be shown that the principal can design contract parameters, $\{u_t(\tilde\theta), w_t(\tilde\theta)\}_t$, such that if the manager maximizes

$$\sum_{t=1}^{T} \gamma^{t-1}\big[w_t(\tilde\theta) + u_t(\tilde\theta) RI_t - z_t h_t(\theta)\big],$$

he will select $z^*(\theta)$ for each θ and earns the second-best information rent given in (16).

Suppose for now that the manager has truthfully reported $\tilde\theta = \theta$. Given Assumption 1, the proof of Proposition 2 has demonstrated that compounded historical cost valuation with LIFO costing ensures that $\max_{s_t, q_t}\{RI_t(\cdot \mid z_t)\} = B_t(z_t)$ for all $t \notin I$, and $\max_{q_t, x_{\tau t}}\{RI_t(\cdot \mid z_t)\} = B_t(z_t)$ for all $t \in I$, with $B_t(z_t)$ as defined in (14). Thus, the manager solves: $\max_{\{z_t\}_t} \sum_{t=1}^{T} \gamma^{t-1}[u_t(\theta)B_t(z_t) - z_t h_t(\theta)]$. If the contract parameters are chosen such that

$$u_t(\theta) = u_t^*(\theta) = \frac{h_t(\theta)}{H_t(\theta)},$$

$$w_t(\theta) = w_t^*(\theta) = \int_\theta^{\bar\theta} z_t^*(\xi) h_t'(\xi)\, d\xi - [u_t^*(\theta) B_t(z_t^*(\theta)) - z_t^*(\theta) h_t(\theta)],$$

it is readily verified that the manager will indeed select $z_t = z_t^*(\theta)$ for all t and his informational rent is equal to that in Equation (16) (Revenue Equivalence Theorem).

To demonstrate that the proposed delegation mechanism is globally incentive compatible (local incentive compatibility is ensured by construction of the above contract parameters), let

$$U(\tilde\theta, \theta) \equiv \sum_{t=1}^{T} \gamma^{t-1} W_t(\tilde\theta, \theta)$$

denote the manager's utility under this contract, where for $t = 1, \ldots, T$,

$$W_t(\tilde\theta, \theta) \equiv u_t^*(\tilde\theta) B_t(z_t(\tilde\theta, \theta)) - z_t(\tilde\theta, \theta) h_t(\theta),$$
$$\{z_t(\tilde\theta, \theta)\}_{t=1}^{T} \in \arg\max_{\{z_t\}} \sum_{t=1}^{T} \gamma^{t-1}\big[u_t^*(\tilde\theta) B_t(z_t) - z_t h_t(\theta)\big]. \qquad \text{(A8)}$$

Thus, $\{z_t(\tilde\theta, \theta)\}_t$ is the sequence of productivity parameters chosen by the manager if he has reported $\tilde\theta$ while actually being of type θ. Invoking a result from Mirrlees (1986), a locally incentive compatible mechanism is also globally incentive compatible, if $(\partial/\partial\theta) U(\tilde\theta, \theta)$ is (weakly) increasing in $\tilde\theta$ for all t. By the Envelope Theorem,

$$\frac{\partial}{\partial\theta} W_t(\tilde\theta, \theta) = -z_t(\tilde\theta, \theta) h_t'(\theta).$$

A necessary and sufficient condition for $(\partial/\partial\theta) W_t(\tilde\theta, \theta)$ to be weakly increasing in $\tilde\theta$ thus is that $z_t(\tilde\theta, \theta)$ is nonincreasing in $\tilde\theta$. Denoting $\Gamma_t(\tilde\theta, \theta, z_t) \equiv u_t^*(\tilde\theta) B_t(z_t) - z_t h_t(\theta)$, a sufficient condition for $\hat z_t(\tilde\theta, \theta)$ to be nonincreasing in $\tilde\theta$ is that

$$\frac{\partial^2}{\partial z_t \partial\tilde\theta} \Gamma_t(\tilde\theta, \theta, z_t) = u_t^{*'}(\tilde\theta) B_t'(z_t) \le 0.$$

This indeed holds, because $B_t'(z_t) \ge 0$ and $u_t^{*'}(\tilde\theta) \le 0$, by Assumption 2, completing the proof of Proposition 2′. $\square$

[29] We assume that the range of μ is sufficiently small so that, provided $x_1^*(z)$ was chosen optimally, the marginal revenue evaluated at the optimal sales quantity is always positive; i.e., for all μ, z: $R_2'(s_2^*(x_1^*(z) \mid z_2, \mu) \mid z_2, \mu) > 0$ and $R_3'(s_3^*(x_1^*(z) \mid z_3, \mu) \mid z_3) > 0$. As a consequence, $s_3^*(\cdot) \equiv x_1^*(z) - s_2^*(\cdot)$.

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