The Impact of Unit Cost Reductions on Gross Profit:

Increasing or Decreasing Returns? #

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# Comments on the research from Professors John R. Hauser and Birger Wernerfelt have been most helpful.
Abstract

When asked about the impact of unit manufacturing cost reductions on gross profit, many managers and academics assume that returns will be diminishing, i.e., that the first cent of unit cost reduction will generate more incremental gross profit than the last cent of unit cost savings, consistent with the economic intuition about diminishing returns. (The product’s appeal to the market is assumed to remain constant.) The present paper shows why gross profits actually increase in a convex fashion under typical demand assumptions, providing increasing returns with each additional cent of reduction in unit manufacturing cost. The intuition is that if \( q \) units are sold at the current price, the first cent of unit cost reduction increases the gross profits by \( q \) cents (keeping the price at the current level). But further cost reductions bring about greater pricing flexibility so that the optimal price decreases, thereby increasing the quantity to \( q' \). Thus, the last cent of cost reduction produces an incremental profit of \( q' \) cents, where \( q' > q \). The convex returns are captured graphically in the “profit saddle,” a simple plot of gross profit as a function of unit cost and unit price. Decreasing unit costs produce additional returns from learning curve effects, reduced per unit channel costs, quality improvements, and strategic considerations. Of course, the fixed investment entailed in reducing unit-manufacturing costs must be weighed against the returns from doing so, suggesting some optimal level of unit cost reduction efforts.

Cost reduction has traditionally been the purview of the manufacturing function within the firm, and has been emphasized in the later phases of the product-process life cycle. Marketing managers, on the other hand, have focused on generating sales revenues through pricing, product positioning, promotion, and channel placement. The present paper suggests that the traditional view be questioned. The marketing function, and new product planning in particular, may want to consider unit manufacturing cost reduction a potent tool in pricing new products for marketing success.
The Impact of Unit Cost Reductions on Gross Profit: Increasing or Decreasing Returns?

How important are unit manufacturing costs in the design and development of new products? Many questions arise in determining the optimal cost reduction strategy during new product development (NPD). For example, should the marketing members of multifunctional NPD teams be concerned with cost-related decisions even though these issues have traditionally been the purview of the engineering and manufacturing functions of the firm? Our analysis shows that, in many cases, marketers should be involved in these decisions from the outset, consistent with prior research on the need for integration between marketing and manufacturing during NPD (Wheelwright and Clark 1992, Griffin and Hauser 1996, Kahn 1996). What is the profit impact of reducing unit manufacturing cost - do incremental cost reductions yield increasing or diminishing returns? We show that, contrary to the economic intuition of diminishing returns, cost reductions yield increasing returns.

Further, how should cost reduction proceed and how much investment in cost reduction is optimal? We show conditions under which an optimal level of investment in unit cost reduction may be identified. Of course the “real” answer here is more complex, and we suggest that careful concept selection (e.g. Altschuler 1996, Pugh 1996, Srinivasan, Lovejoy, and Beach 1997, Dahan and Srinivasan 2000, Dahan and Mendelson 2001), target costing (Chew and Cooper 1996), design for manufacturability and assembly (Boothroyd, Dewhurst, and Knight 1994), set-based methodologies (Ward, Liker, Cristiano and Sobek 1995), operational efficiency (Imai 1986, Lee 1996), and the use of postponement (Feitzinger and Lee 1997), modularity (Baldwin and Clark 2000), and platforms (Meyer and Lehnerd 1997, Ulrich and Eppinger 2000)
can all contribute. These approaches complement the direct benefits of investing in unit cost reduction achieved through clever design.

In this paper, we focus on the nature of the impact of unit cost reduction on gross profits. Our findings regarding the profit impact of cost reduction efforts run counter to many managers’ and academics’ intuitions. We find that early and effective cost savings efforts may improve the chances of new product success to a greater extent than is commonly believed, and that the payoff from unit cost reduction justify significant investment in “smarter” design during the NPD process (Ulrich and Pearson 1998). In fact, the potential for unit cost reduction may be an important criterion when selecting a new product concept from amongst competing ideas.

1 Increasing, Linear or Decreasing Returns?

Consider the three possibilities depicted in Figure 1. In all cases, the product in question is assumed to remain constant in the perceptions of customers. That is, any changes required to achieve unit cost reductions are assumed to have no effect on the desirability of, willingness-to-pay for, or probability of purchase of the product at any given price. For instance, cost reductions may be brought about by design for manufacturability and assembly (Boothroyd, Dewhurst and Knight 1994) or by sourcing through lower cost suppliers, neither of which alter the functionality or appearance of the product.

In the lower (dotted) curve, investments in unit cost reduction improve gross profit, defined as revenues minus variable direct costs, exhibit diminishing returns. That is, the first cent of unit cost reduction has a greater impact on gross profit than the next cent of cost reduction. This fits the general economic intuition of diminishing returns. The middle (solid) line depicts a linear relationship between cost reduction and profit, consistent with the idea that
unit costs do not necessarily affect revenues, so the firm reaps additional profits from cost reduction only in the form of higher unit margin, which goes up linearly with cost reduction. This is consistent with the notion that prices should not vary based on costs, but rather on “what the market will bear.”

Figure 1: Do unit cost reductions yield increasing, constant, or decreasing returns?

Finally, the upper (dashed) curve depicts increasing returns, implying that cost reduction produces benefits beyond simple unit margin improvements at existing volumes, and that prices and volumes must adjust to unit cost reductions in order to maximize profit. It is this third, somewhat counterintuitive, scenario that is supported by the following economic analysis. Our proof of the convexity (increasing returns) of gross profit as a function of unit cost reduction rests on four assumptions.
Assumptions:

- **[A1] Proportional Costs:** Total Variable Cost \((TVC)\) is proportional to quantity \((q)\), so that \(TVC(q) = c \cdot q\), where \(c\) denotes the unit (variable) cost.

- **[A2] Downward Sloping Demand:** The quantity demanded, \(q(p)\), is a monotonically decreasing function of price \((p)\): i.e., \(\frac{\partial q}{\partial p} < 0 \ \forall \ p\).\(^1\)

- **[A3] Unique Profit-maximizing price:** For any given unit cost \(c\), the gross profit function, \(\pi = [p \times q(p)] - TVC(q)\), is strictly quasi-concave and smooth in \(p\), and therefore has a unique, profit-maximizing price, \(p^*\), at which point the function is locally strictly concave, i.e., \(\frac{\partial^2 \pi}{\partial p^2} < 0\) at \(p^*\). (cf., Figure 2).

- **[A4] Positive Gross Profit:** Unit cost, \(c\), is such that the optimal gross profit is strictly positive, i.e., \(p^* > c\) and \(q(p^*) > 0\).

**Figure 2:** Profit is maximized at a unique price which depends on unit cost

Figure 2 illustrates the process by which an optimal price is set based on the unit cost of the product. The figure shows the effects of having two possible unit costs, \(c_{\text{high}}\) and \(c_{\text{low}}\), for a product that is identical as perceived by consumers.

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\(^1\) This assumption does not imply that we consider only the case of pure monopoly. In the case of competition with differentiated products, we assume that the price reactions of competitors to the firm’s price change are such that the net effect on quantity is monotonic, as stated.
Note that gross profits are consistently higher under the $c_{low}$ regime as would be expected. Note also that the gross-profit-maximizing price, $p^*$, differs between the two scenarios, and is lower under the lower-cost regime. For a given unit cost, gross profit declines to the left of $p^*$ since the unit margin is reduced too much, and declines to the right of $p^*$ because the sales volume is reduced too much. Thus, $p^*$ represents the point at which the tension between unit gross margin and total volume is optimized.

Using the above four assumptions, we first show that optimal prices strictly decrease when cost reductions are achieved. That is, it is optimal to pass on unit cost reductions to consumers to at least some extent.

**Lemma:** The optimal price is increasing in cost, i.e., $\frac{dp^*}{dc} > 0$.

**Proof:** The first order condition (FOC) for maximizing the gross profit function shown in [A3] by setting price optimally is:

$$
(1) \quad FOC = \frac{\partial \pi}{\partial p} = \frac{\partial [(p-c) \times q(p)]}{\partial p} = (p-c) \frac{\partial q}{\partial p} + q(p) = 0.
$$

By invoking the Implicit Function Theorem at $p^*$, we see that:

$$
(2) \quad \frac{dp^*}{dc} = -\frac{\partial FOC/\partial c}{\partial FOC/\partial p} = \frac{\partial q/\partial p}{\partial^2 \pi/\partial p^2} > 0,
$$

since $\frac{\partial q}{\partial p} < 0$ by [A2] and $\frac{\partial^2 \pi}{\partial p^2} < 0$ at $p^*$ by [A3].
Thus when pricing optimally, and given our assumptions, unit cost reductions lead to strictly lower prices.

Employing the Lemma, we now show that gross profits exhibit increasing returns to cost reduction. That is, \( \pi \) is convex in \( c \).

**Theorem:** For any demand function, \( q(p) \), meeting assumptions [A1] - [A4], the optimal gross profit, \( \pi(p^*, c) = (p^* - c) \times q(p^*) \) is strictly decreasing and strictly convex in unit cost, \( c \).

That is, \( \frac{d^2 \pi(p^*, c)}{dc^2} > 0 \). Consequently, gross profit returns to unit cost reductions are strictly increasing and strictly convex.

**Proof:** Differentiating \( \pi(p^*, c) = (p^* - c) \times q(p^*) \) with respect to \( c \), we have

\[
\frac{d\pi(p^*, c)}{dc} = \frac{\partial \pi}{\partial c} + \frac{\partial \pi}{\partial p^*} \frac{dp^*}{dc}
\]

\[
= -q(p^*) + \frac{\partial \pi}{\partial p^*} \frac{dp^*}{dc}
\]

\[
= -q(p^*)
\]

since, by the first order condition (1), \( \frac{\partial \pi}{\partial p^*} = 0 \). From the fact that \( q(p^*) > 0 \) in [A4] it follows that profit is strictly decreasing in \( c \), i.e. that profit is strictly increasing with cost reductions. Differentiating (3) one additional time, we get

\[
\frac{d^2 \pi(p^*, c)}{dc^2} = -\frac{\partial q}{\partial p^*} \frac{dp^*}{dc}.
\]

Since \( \frac{\partial q}{\partial p^*} < 0 \) by [A2] and \( \frac{dp^*}{dc} > 0 \) by the Lemma, \( \frac{d^2 \pi(p^*, c)}{dc^2} > 0 \).
The profit convexity result of Theorem 1 is intuitively explained by Figure 3.

**Figure 3: Intuition Underlying Profit Convexity**

When unit cost is high before cost reduction efforts, as at $c_{high}$, the optimal price is correspondingly high (Lemma 1) and the sales volume is therefore low. Thus, reducing a high unit cost by 1 cent has a small effect on gross profit since the volume being sold is small. When unit cost is much lower after significant cost reduction, as at $c_{low}$, the impact is greater since the same 1-cent saving applies to a higher volume of units sold since the optimal price will now be lower. The higher volumes resulting from lower prices may derive from both greater per customer consumption and a greater number of customers when price is lowered.

Another way of intuitively seeing the convexity result is to observe that if the price is held constant, gross profit increases linearly with the amount of unit cost reduction. Beyond this direct benefit of cost reduction, the firm has the flexibility to change its price with any reduction in cost, and garner an indirect benefit from pricing flexibility. Because this added flexibility, if optimally exercised, can only increase gross profits over and above the direct linear improvement, the profit curve will be higher than the tangent to the curve. Because this
phenomenon holds true for every value of unit cost, the profit curve is a convex-increasing function of the amount of unit cost reduction.

Assumptions [A2] through [A4] are reasonable in that they are likely to hold in most situations. However, assumption [A1] states that the total variable cost ($TVC$) is proportional to the quantity ($q$), $TVC(q) = c \cdot q$. In the Appendix we show that the Lemma and Theorem continue to hold in the presence of non-linear cost curves (e.g., economies of scale) of the form $TVC(q) = c \cdot f(q)$, where $f(q) > 0$, $f'(q) > 0$ and $c$ is a cost parameter that can be reduced.\(^2\) (In order to make the parameter $c$ refer to the marginal cost at $q = 0$, the function $f(q)$ is defined so that $f(0) = 0$ and $f'(0) = 1$.) See Figure 4 in the context of a cost curve exhibiting economies of scale. (However, we note that $f(q)$ need not be concave.)

![Figure 4: Non-Linear Cost Curves](image)

\(^2\) We assume that the function $f(q)$ is such that assumption [A3] holds.
We now analyze two well-known demand functions, linear demand and constant elasticity, to illustrate the result.

**Example 1: Linear Demand**

As a simple example of increasing returns, consider a monopolist facing a demand curve that is linear in price, \( 0 \leq p < 1 \), with \(-m\) being the slope of the demand curve, \(c\) being the constant marginal cost of production (\(0 \leq c < p\), consistent with [A4]), and \(q\) the quantity sold.

Linear Demand Function: \( q = m \times (1 - p) \)

Profit: \( \pi = (p - c) \times m \times (1 - p) \)

To maximize profit, \(\pi\), the firm sets its price at \( p^* = \frac{c + 1}{2} \) and realizes profits of

\[
\pi^*(c) = m \times \frac{(1 - c)^2}{4} \text{ at } q^* = \frac{m \times (1 - c)}{2}.
\]

Thus, \( \frac{d\pi^2(c)}{dc^2} = \frac{m}{2} > 0 \) (i.e. \(\pi\) is convex in \(c\)). The second derivative of profit with respect to unit cost is positive for the negatively sloped linear demand function, thus confirming increasing returns to unit cost reductions. As expected, cost reductions lead to price reductions \( \left( \frac{dp^*}{dc} > 0 \right) \), and volume increases \( \left( \frac{dq^*}{dc} < 0 \right) \).

**Example 2: Constant Elasticity Demand**

Similarly, the firm may face demand with constant price elasticity, \(\varepsilon\).

Demand Function: \( q = kp^{-\varepsilon} \),

Profit: \( \pi = (p - c) \times kp^{-\varepsilon} \)
To maximize profit, $\pi$, the firm sets its price at $p^* = c \times \left( \frac{\varepsilon}{\varepsilon - 1} \right)$ with

$$q^* = k \times \left( \frac{\varepsilon}{\varepsilon - 1} \right)^{-\varepsilon} c^{-\varepsilon},$$

and realizes profits of $\pi^*(c) = \frac{K}{c^{\varepsilon - 1}}$, where $K = \frac{k\varepsilon^{-\varepsilon}}{(\varepsilon - 1)^{\varepsilon + 1}}$. Note that $\varepsilon > 1$ in order to satisfy [A4]. The second derivative of profit with respect to unit cost is

$$\frac{d\pi^2(c)}{dc^2} = K(\varepsilon - 1)(\varepsilon) \cdot c^{-\varepsilon - 1} > 0,$$

which is positive for any elasticity greater than one, again confirming increasing returns to unit cost reductions. Again, cost reductions lead to price reductions $\left( \frac{dp^*}{dc} > 0 \right)$, which lead to volume increases $\left( \frac{dq^*}{dc} < 0 \right)$.

**Figure 5: The Profit Saddle**

The relationship between unit cost, optimal price and gross profit is illustrated graphically in Figure 5, which we label “The Profit Saddle”. Note that optimal prices decrease as unit costs decrease. The convexity result shows up as the ridge of the saddle (dotted line), and comprises the set of points at which profit is optimized for each possible unit cost.
2 Additional Benefits of Cost Reduction

Beyond the cost-price-profit relationship captured by Theorem 1 and the Profit Saddle of Figure 5, there are four additional benefits of designing in lower unit costs early in the new product development process: (1) accelerated learning, (2) reduced per unit channel cost, (3) fewer defects, and (4) strategic benefits.

**Added Benefit 1: Learning Curve Virtuous Cycle**

The Learning Curve, the phenomenon by which cumulative production volumes lead to ongoing decreases in unit cost, as in Figure 6 (Abernathy 1978), implies that higher volumes (from lower prices) may lead to accelerated learning and further cost reduction.

![Figure 6: the Learning Curve](image)

As illustrated in Figure 7, starting off with a lower unit cost through careful design choices early in the NPD process leads to a virtuous cycle in which higher volumes are produced faster.

![Figure 7: Learning Curve Virtuous Cycle](image)

Lower unit costs at the design phase give the firm a “head start” on the competition in its race down the learning curve, and translates into a higher net present value of future gross profits.
Added Benefit 2: Reduced Unit Channel Cost

Unit cost reduction may reduce unit channel cost by virtue of increased volume. Wholesalers and retailers, a significant portion of whose costs does not vary directly with volume, may now amortize their fixed costs over a larger volume of the product, thereby reducing the per unit cost of distribution. The channel may pass on some of these savings to consumers, further stimulating sales volume.

Added Benefit 3: Reduction in Defects

Unit cost reduction may, ironically, improve product quality. While intuition might dictate that lower unit cost implies lower quality, research (Barkan and Hinkley 1994, Mizuno 1988, Taguchi 1987) has demonstrated that cost reduction efforts aimed at reducing the number of parts and making assembly more efficient also reduce the number of failure modes of the product, thereby reducing defects. See Figure 8.

**Figure 8: Cost Reduction Produces Fewer Defects**

![Effect of Assembly Efficiency on Quality](image)

From Barkan and Hinkley (1994)

Figure 9 provides data from the leaders in design for manufacturing and assembly, Boothroyd and Dewhurst, claiming that efforts at reducing unit costs through design for manufacturing and assembly (DFMA) not only reduce costs through faster assembly and fewer...
parts, but also reduce assembly defects and the need for service calls, consistent with the improved quality argument above.

**Figure 9: Improvements from Design for Manufacturability and Assembly (DFMA)**

![Improvements from Design for Manufacturability and Assembly (DFMA)](image)


They further make the claim that time-to-market may also be halved since the process of ramping up production becomes much easier when the product design has been simplified for manufacturability (Smith and Reinertsen 1998). Clearly, if product quality and reliability are improved and time-to-market is shortened, profits should improve as well.

**Added Benefit 4: Keeping Competitors Out of the Market**

Unit cost reduction provides potential strategic benefits as depicted in Figure 10, based on research by Schmidt and Porteus (2001).

**Figure 10: The Strategic Benefit of Cost Reduction**

![The Strategic Benefit of Cost Reduction](image)

From Schmidt and Porteus (2001)
When the firm establishes itself as the low cost manufacturer, it dissuades competitors from entering the market, leading to significantly higher profits. The ability to develop and manufacture products at lower unit costs than competitors, here captured by the cost competence factor, $C$, may be as important as the ability to develop more innovative products, captured by $R$. By being competent at unit cost reduction, incumbent market leaders are able to keep potential entrants at bay.

3 Optimal Cost Reduction

Having established the increasing returns to unit cost reduction, one must weigh this against the “costs of cost reduction,” which take the form of investments that are independent of the volume of products sold. These investments take many forms, each of which may contribute to the overall reduction in unit cost. For example, design for manufacturing and assembly (DFMA), process automation, operational efficiency and variance reduction, and improved purchasing have cumulative effects on unit cost reduction. Analytically, these potential investments can be summarized by a function as depicted by the dashed curve in Figure 11.

**Figure 11: Profit is Optimized When Marginal Gross Profit Equals Marginal Investment**

![Diagram showing optimal cost reduction and investment](image-url)
The dashed curve relates the level of investment in cost reduction efforts, amortized to coincide with the time frame used in the unit gross profit contribution analysis, to their effect on unit costs. We assume that such investments are made optimally to achieve the greatest amount of cost reduction for the least amount of investment, making the function convex (i.e. earlier investments have higher payoffs). We further assume that the degree of convexity of the investment function is greater than that of the gross profit returns to unit cost reduction, the dotted line in Figure 11.

Under the above conditions, there exists a unique level of investment in unit cost reduction at which net profits, that is gross profit contribution minus the (amortized) investment in cost reduction, is maximized. This occurs at the point where the marginal benefit of reducing the unit cost is equal to the marginal (amortized) investment required to achieve that unit cost. Of course, a richer analysis factoring in the added benefits of unit cost reduction and more richly detailed investment function might produce a less “clean” result, but the analysis would proceed along much the same lines.

In summary, unit cost reduction has been shown to have increasing returns due to the attendant price reductions and increased volume, and additional benefits due to the virtuous cycle of the learning curve, reduced channel costs, potential quality improvements, and strategic effects. These benefits should be carefully evaluated and traded off against the investment required to achieve unit cost reductions. While unit cost reduction efforts during NPD have traditionally been the purview of manufacturing personnel in the firm, these analyses suggest that their impact offers a pricing advantage when developing new products for future marketing success.
Appendix

Lemma (Non-linear Cost function): Given the Total Variable Cost Function, \( TVC(q) = c \cdot f(q) \), with \( f(q) > 0 \) and \( f'(q) > 0 \), the optimal price \( p^* \) is increasing in the cost parameter \( c \), i.e., \( \frac{dp^*}{dc} > 0 \).

Proof: The gross profit \( \pi = p \cdot q(p) - c \cdot f(q(p)) \). The first order condition (FOC) for maximizing \( \pi \) by setting price optimally is:
\[
FOC = \frac{\partial \pi}{\partial p} = p \ q'(p) + q(p) - c \times f'(q) \ q'(p) = 0.
\]
By invoking the Implicit Function Theorem at \( p^* \), we see that:
\[
\frac{dp^*}{dc} = -\frac{\partial FOC}{\partial c} = \frac{f'(q) \ q'(p)}{\partial \pi^2 / \partial p^2} > 0,
\]
since \( f'(q) > 0, q'(p) < 0 \) by Assumption [A2], and \( \frac{\partial^2 \pi}{\partial p^2} < 0 \) at \( p^* \) by [A3]. Thus \( \frac{dp^*}{dc} > 0 \). #

Theorem (Non-linear Cost function): Given the Total Variable Cost Function, \( TVC(q) = c \cdot f(q) \), with \( f(q) > 0 \) and \( f'(q) > 0 \), the profit function is convex in the cost parameter \( c \), i.e., \( \frac{d^2 \pi (p^*, c)}{dc^2} > 0 \).

Proof: \( \pi (p^*, c) = p^* \cdot q(p^*) - c \cdot f(q(p^*)) \).
\[
\frac{d \pi (p^*, c)}{dc} = \frac{\partial \pi}{\partial c} + \frac{\partial \pi}{\partial p^*} \frac{dp^*}{dc} = \frac{\partial \pi}{\partial p^*} = 0 \text{ by the } FOC.
\]
\[
\frac{d^2 \pi (p^*, c)}{dc^2} = -f[q(p^*)] < 0
\]
\[
\frac{d^2 \pi (p^*, c)}{dc^2} = -f[q(p^*)] q'(p^*) \frac{dp^*}{dc}
\]
Because \( f'(q) > 0, q'(p) < 0 \) (Assumption [A2]), and, \( \frac{dp^*}{dc} > 0 \) (Lemma), it follows that \( \frac{d^2 \pi (p^*, c)}{dc^2} > 0 \), i.e., that \( \pi \) is convex in \( c \). #
References


