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On cost-cutting incentives

Sreya Kolay
University at Albany, SUNY

Abstract

Reducing costs remains an important objective of business strategy, driving choices such as production process redesign, technology adoption, and outsourcing. This paper examines how the intensity of price competition affects firms' marginal benefits from lowering per-unit variable costs in a differentiated-products duopoly. Applying the conjectural-variations framework, we show that symmetric firms face a non-monotonic relationship between competitive intensity and their marginal benefits from cost reduction. In contrast, when there are significant asymmetries in firms' initial costs, this relationship becomes monotonic, which may differ in directions across competing firms. We also show that while higher competitive intensity increases the social welfare gain from a firm's cost reduction in case of symmetric firms, it can increase or decrease the social welfare change from a firm's cost reduction in case of asymmetric firms.

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Contact: Sreya Kolay - skolay@albany.edu.
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1. Introduction

Reducing costs remains an important goal of business strategy (Porter 1985), underpinning such decisions as production process redesign (e.g., Hammer 2007), information-systems adoption (e.g., Melville et al. 2004), outsourcing (e.g., Lacity et al. 2010), and artificial intelligence adoption (e.g., McElheran et al. 2025). Given the strategic importance and significant costs of these initiatives, it is important to understand how a firm's benefits from these activities relate to firm-level and industry-level characteristics. Understanding such links is not only important for firms choosing to invest in cost-reduction activities, but also for providers of cost-reducing services, as it helps them identify which firms benefit more from their services.

In this paper, we examine the link between firms' marginal private benefits from reducing their per-unit variable costs and the intensity of price competition in the industry, as proxied by the conjectural-variations parameter. In a linear differentiated-products oligopoly, we show that if the firms are symmetric, then the marginal benefit of cost reduction is non-monotonic in the intensity of price competition. We then examine the case of an asymmetric duopoly where one firm starts out with a production-cost advantage over the other firm. We show that if the asymmetry in starting costs is small, then the results from the symmetric-firms case continue to hold. However, if the starting asymmetry is large, then the marginal benefits from cost reduction for the firms become monotonic in the intensity of competition – decreasing for one firm and increasing for the competing firm. Finally, we also examine how intensity of price competition moderates the effect of a unit-variable cost reduction on social welfare.

Our paper contributes to the theoretical literature that has related firms' cost-reducing incentives to various firm-level and industry-level characteristics. For example, Dasgupta and Stiglitz (1980) show that a firm's investment in cost reduction decreases with the number of competing firms in its market; Spence (1984) shows that a firm invests less in cost reduction if there is a larger spillover of its investment success to competing firms; Rosen (1991) finds that a stronger firm invests more in cost reduction than a weaker firm; Qiu (1997) shows that firms invest less under price competition than under quantity competition; and Vives (2008) shows that cost reduction expenditure per firm decreases with the number of firms and increases with the degree of product substitutability and market size. More recent work continues to examine determinants of firms' cost-cutting incentives, including the role of cost structures (Mishra 2025), product positioning (Bacchiega and Garella 2025), and energy-saving investments (Hirose and Matsumura 2025).

In another strand, Aghion et al. (2001) develop a dynamic step-by-step innovation model in which firms choose the number of innovation steps in each time period and show a non-monotonic relation between innovation and competitive pressure due to "escape-competition" and "Schumpeterian" effects. Boone (2000) analyzes how greater competitive pressure shifts investment toward process (cost-reducing) innovation and away from product innovation at the industry level, showing that a rise in competitive pressure cannot raise both simultaneously. Boone (2008) models tougher competition as reallocation toward more efficient firms via a profit-elasticity metric, showing that higher competitive toughness disproportionately benefits low-cost firms (a selection effect). More recently, Aghion et al (2018) present experimental evidence on the causal effect of competition on innovation incentives.

Unlike these prior studies, we focus on static cost-reducing incentives in a linear differentiated-products price oligopoly and operationalize competitive intensity with a conjectural-variations parameter. Our contribution is to characterize the marginal private benefit of a small reduction in a firm's unit (variable) cost as a function of competitive intensity: we obtain a non-monotonic (hump-shaped) relationship under symmetry and, with sufficiently large initial cost asymmetry, opposing monotonic effects (increasing for the cost-advantaged firm and decreasing for the cost-disadvantaged firm).

2. The Model

We consider a market with two firms, and use the following commonly-used demand function of Shubik and Levitan (1980):[1]

$$q_i(p_i, p_j) = \frac{1}{2}\left[1 - p_i + \beta\left(\overline{p} - p_i\right)\right], \qquad i, j = 1, 2;\ i \neq j. \tag{1}$$

Here q_i is firm i's sales, p_i is its price, $\overline{p}$ the average market price, and $\beta \in [0, \infty]$ measures the degree of product substitutability, with a higher value of β associated with more substitutable products. As shown in Shubik and Levitan, this demand function derives from the following utility function of a representative consumer:

$$U\left(q_1, q_2\right) = \sum_{i=1}^{2} q_i - \frac{1}{2\left(1+\beta\right)}\left[\sum_{i=1}^{2} q_i^2 + \beta\left(\sum_{i=1}^{2} q_i\right)^2\right] + I$$

where I is the numeraire good.

To parsimoniously model different intensities of price competition in the market, we use the conjectural-variations parameter, $\theta \equiv \partial p_j / \partial p_i,\ i, j = 1, 2;\ i \neq j$. As shown in prior research (e.g., Bresnahan 1989), the parameter θ can be interpreted as the degree to which each firm internalizes its competitor's profit in setting prices. It can be used to index competitive intensity: $\theta = 0$ corresponds to Bertrand-Nash competition, $\theta = 1$ to perfectly collusive conduct, and $\theta \in (0, 1)$ captures intermediate competitive intensities, with higher θ representing less intense competition. Dockner (1992), Cabral (1995), and Pfaffermayer (1999), among others, establish that this formulation provides a reduced-form representation of competitive intensity in broader dynamic firm interactions.

More recent literature also uses conjectural variations in strategic settings such as delegation decisions in competitive markets (Ciarreta and Garcia-Enriquez 2018), and investment incentives in electricity spot markets (Mousavian et al. 2020). In empirical work, the conjectural-variations approach is widely used to measure competition intensity (e.g., Genesove and Mullin 1998, Graf and Wozabal 2013, Ruiz-Moreno et al. 2021, Fladung and Saile 2024, Sheng and Vukina 2025).

The profit function of firm i is $\pi_i = (p_i - c_i)\, q_i$ where q_i is as in (1). The first-order

[1] We verify that all our results qualitatively also hold for the popular Vives demand function.

conditions for profit maximization are:

$$(p_i - c_i)\left[\frac{\partial q_i}{\partial p_i} + \theta\frac{\partial q_i}{\partial p_j}\right] + q_i = 0, \quad i, j = 1, 2;\ i \neq j.$$

Solving these two conditions using (1), we get the following equilibrium outcomes

$$p_i = c_i + \frac{(1+\beta)(c_j - c_i)}{4+\beta(3-\theta)} + \frac{2 - c_i - c_j}{4+\beta(1-\theta)}, \tag{2}$$

$$q_i = \frac{[2+\beta(1-\theta)]\left[8(1-c_i) + 2\beta\{3 + c_j - c_i(4-\theta) - \theta\} + \beta^2(c_j - c_i)(1-\theta)\right]}{4[4+\beta(3-\theta)][4+\beta(1-\theta)]}, \tag{3}$$

$$\pi_i = \frac{[2+\beta(1-\theta)]\left[8(1-c_i) + 2\beta\{3 + c_j - c_i(4-\theta) - \theta\} + \beta^2(c_j - c_i)(1-\theta)\right]^2}{4[4+\beta(3-\theta)]^2[4+\beta(1-\theta)]^2}. \tag{4}$$

We need the following conditions on the absolute and relative values of per-unit variable costs to ensure that both firms have positive prices, sales, and profits:

$$c_1 < 1, \text{ and } c_2 - c_1 = \Delta < \overline{\Delta}_1(\beta) = \frac{2(1-c_1)[4+\beta(3-\theta)]}{8+\beta(8+\beta) - \beta\theta(2+\beta)}. \tag{5}$$

From (4), we get the marginal return from reduction in per-unit variable cost, $MR_i = \partial\pi_i/\partial c_i =$

$$-\frac{[2+\beta(1-\theta)][8+\beta(8+\beta)-\beta\theta(2+\beta)]\left[8(1-c_i) + 2\beta\{3 + c_j - c_i(4-\theta) - \theta\} + \beta^2\Delta(1-\theta)\right]}{2[4+\beta(3-\theta)]^2[4+\beta(1-\theta)]^2}, \tag{6}$$

which, as expected, is negative for $\Delta < \overline{\Delta}_1(\beta)$, where $\overline{\Delta}_1(\beta)$ is the largest allowable value of $\Delta = c_2 - c_1$ by (5). That is, each firm always benefits from reduction in its per-unit variable cost.

Given that $MR_i = \partial\pi_i/\partial c_i$ is negative in sign, the absolute value of MR_i, $|MR_i|$, represents the marginal return from cost reduction and is the measure that we will use in our analysis.

3. Symmetric Firms

We first examine how the marginal return from cost reduction changes with the intensity of price competition (θ) for symmetric firms, i.e., when $c_j = c_i = c$. Here, the conditions for positive sales for both firms given in (5) reduce to $c < 1$.

Differentiating (6) w.r.t. θ, and then setting $c_j = c_i = c$, we get

$$\frac{\partial|MR_i|}{\partial\theta} = (1-c)\left[\frac{(1+\beta)^2}{[4+\beta(3-\theta)]^2} - \frac{4\beta}{[4+\beta(1-\theta)]^3} - \frac{1}{[4+\beta(1-\theta)]^2}\right].$$

We find that $\partial|MR_i|/\partial\theta \gtreqless 0$ for $\theta \lesseqgtr \theta_1(\beta)$, where $\theta_1(\beta) \in (0,1)$. The expression for $\theta_1(\beta)$ is given in the Appendix.

Thus we have the following result.

Proposition 1 (Symmetric Firms): *The marginal returns from cost reduction for symmetric firms are non-monotonic in the intensity of competition. Specifically, an increase in competitive intensity raises the marginal return from cost reduction in less competitive markets but lowers it in more competitive markets.*

This result arises because an increase in competitive intensity has opposing effects on (i) the price-margin gain, and (ii) the sales gain from passing through the reduction in its marginal cost. In markets with higher competitive intensity, demand is more elastic. Therefore, a price cut leads to a larger increase in sales, implying a stronger sales-gain effect with higher competitive intensity. At the same time, the price-margin gain is smaller with higher competitive intensity because the firms' markups are lower as competition becomes more intense. Thus, when competitive intensity is high, the sales gain effect dominates. Conversely, when competitive intensity is weaker, firms' pass-through of cost reduction is limited and their markups are higher, implying stronger price-margin gains. Demand on the other hand is relatively less elastic and hence the sales gain effect is weaker. Here, the price-margin gain effect dominates. Thus, the largest gain from a cost reduction occurs when the intensity of competition is neither too low nor too high.

■ **Robustness to n>2 firms.** Consider the case where there are $n > 2$ firms in the market. The Shubik-Levitan utility and demand functions corresponding to (1) are

$$\begin{aligned} U(q_1, ...q_n) &= \sum_{i=1}^{n} q_i - \frac{1}{2}\left(\sum_{i=1}^{n} q_i\right)^2 - \frac{n}{2(1+\beta)}\left[\sum_{i=1}^{n} q_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} q_i\right)^2\right] + I, \text{ and} \\ q_i(p_1, ...p_n) &= \frac{1}{n}\left[1 - p_i + \beta(\overline{p} - p_i)\right]. \end{aligned}$$

The corresponding optimal price and profit are:

$$p_i^* = \frac{1 + S(\theta)c_i + \beta\left(\frac{1+S(\theta)\overline{c}}{1+S(\theta)}\right)}{1+\beta+S(\theta)}, \quad \pi_i^* = \frac{S(\theta)}{n}\left(\frac{1+\beta\left(\frac{1+S(\theta)\overline{c}}{1+S(\theta)}\right) - (1+\beta)c_i}{1+\beta+S(\theta)}\right)^2 \tag{7}$$

where $\overline{p} = \frac{1}{n}\sum_{i=1}^{n} p_i$, $\overline{c} = \frac{1}{n}\sum_{i=1}^{n} c_i$ and $S(\theta) = 1 + \frac{\beta(1-\theta)(n-1)}{n}$. For n symmetric firms, we get, using (7), $MR_i = \frac{\partial \pi_i}{\partial c_i}|_{c_i=c} = -\frac{2(1-c)S(\theta)}{n(1+S(\theta))(1+\beta+S(\theta))}\left[(1+\beta) - \frac{\beta S(\theta)}{n(1+S(\theta))}\right] < 0$, and

$$\frac{\partial\left|MR_i\right|}{\partial\theta} = \frac{2\beta(c-1)(n-1)[(1+\beta)n(1+S(\theta))(1+\beta-S(\theta)^2) - \beta S(\theta)(2+2\beta+S(\theta)-S(\theta)^2)]}{n^3(1+S(\theta))^3(1+\beta+S(\theta))^2}.$$

We find that $\partial\left|MR_i\right|/\partial\theta \gtreqless 0$ for $\theta \lesseqgtr \theta_n(\beta)$, where $\theta_n(\beta) \in (0,1)$. The expression for $\theta_n(\beta)$ is given in the Appendix. Thus Proposition 1 is robust to extension to $n > 2$ firms.

We also show in the Appendix that $\frac{\partial|MR_i|}{\partial n} < 0$. Thus, as expected, the marginal return from a unit reduction in marginal cost reduces in number of firms in the market.

■ **Social Welfare.** Social welfare is $SW = U(q_1, ...q_n) - \sum_{i=1} c_i q_i$. Using the optimal prices derived above, we get

$$\begin{aligned} SW^* &= \frac{S(\theta)(1-\overline{c})}{1+S(\theta)} - \frac{S(\theta)^2}{2(1+\beta)} \frac{\left(K(\overline{c})^2 - 2K(\overline{c})(1+\beta)\overline{c} + (1+\beta)^2\overline{c^2}\right)}{(1+\beta+S(\theta))^2} \\ & -\frac{S(\theta)^2\beta(1-\overline{c})^2}{2(1+\beta)(1+S(\theta))^2} - \frac{S(\theta)\left(K(\overline{c})\overline{c} - (1+\beta)\overline{c^2}\right)}{(1+\beta+S(\theta))}, \end{aligned} \tag{8}$$

where $K(\overline{c}) \equiv 1 + \beta\left(\frac{1+S(\theta)\overline{c}}{1+S(\theta)}\right)$ and $\overline{c^2} = \frac{1}{n}\sum\limits_{i=1}^{n} c_i^2$. For symmetric firms, using (8), we obtain $\frac{\partial SW}{\partial c_i}|_{c_i=c} = -\frac{S(\theta)(S(\theta)+2)(1-c)}{n(1+S(\theta))^2} < 0$ and

$$\frac{\partial}{\partial\theta}\left|\frac{\partial SW}{\partial c_i}\right| = -\frac{2\beta(n-1)(1-c)}{n^2(1+S(\theta))^3} < 0.$$

Thus, as expected, social welfare improves with cost reduction. Furthermore, we find the following result:

Proposition 2 (Social Welfare for Symmetric Firms): *The social welfare gain from a firm's cost reduction in the case of symmetric firms is higher in more competitive markets.*

This is because the higher is the competitive intensity, the larger is the reduction in prices of competing firms in response to the price cut of the focal firm (whose cost is lowered). Thus, the larger expansion in output and consumption results in higher social welfare gains.

4. Asymmetric Firms

It is reasonable to expect that competing firms in most industries do not have identical production costs. Differences in firm history, degrees of vertical integration, economies of scope, and other factors lead to cost asymmetries. In this Section, we allow firms' initial costs to differ and show that the non-monotonicity result continues to hold for small cost differences. However, for larger cost differences, the marginal return from cost reduction changes monotonically for both firms, potentially in opposite directions, as competition intensity increases.

Let $c_2 - c_1 = \Delta > 0$, and recall from Section 1 the conditions required for both firms to have positive prices, quantities, and profits: $c_1 < 1$, and $\Delta \leq \overline{\Delta}_1(\beta)$, where $\overline{\Delta}_1(\beta)$ is defined in (5). We refer to firm 1 as the lower-cost, stronger firm, and firm 2 as the higher-cost firm, weaker firm.

The Stronger Firm. Using the expression for marginal return from cost reduction given in (6), we get

$$\frac{\partial\,|MR_1|}{\partial\theta} = \frac{1}{2}\left(\frac{(\beta+1)^2(\beta\Delta - 2c_1 + 2)}{(\beta(\theta-3)-4)^2} + \frac{4\beta(\beta+1)^3\Delta}{(\beta(\theta-3)-4)^3}\frac{-\beta\Delta + 2c_1 - 2}{(\beta(\theta-1)-4)^2} - \frac{4\beta(2c_1+\Delta-2)}{(\beta(\theta-1)-4)^3}\right).$$

We find that (i) $\frac{\partial |MR_1|}{\partial \theta} \gtreqless 0$ for $\theta \lesseqgtr \theta_2(\beta, \Delta, c_1)$ when $\Delta \leq \Delta_2(\beta, c_1)$, and (ii) $\frac{\partial |MR_1|}{\partial \theta} < 0$ for all feasible θ when $\Delta > \Delta_2(\beta, c_1)$. The expressions for $\theta_2(\beta, \Delta, c_1)$ and $\Delta_2(\beta, c_1)$ are provided in the Appendix.

The Weaker Firm. Using the expression for marginal return from cost reduction given in (6), we get

$$\begin{aligned}\frac{\partial |MR_2|}{\partial \theta} &= \frac{1}{2}\left(-\frac{(\beta+1)^2((\beta+2)\Delta + 2(c_1-1))}{(\beta(\theta-3)-4)^2} - \frac{4\beta(2c_1+\Delta-2)}{(\beta(\theta-1)-4)^3}\right. \\ &\left.+\frac{(\beta+2)\Delta+2(c_1-1)}{(\beta(\theta-1)-4)^2} - \frac{4\beta(\beta+1)^3\Delta}{(\beta(\theta-3)-4)^3}\right).\end{aligned}$$

We find that (i) $\frac{\partial |MR_2|}{\partial \theta} \gtreqless 0$ for $\theta \lesseqgtr \theta_3(\beta, \Delta, c_1)$ when $\Delta \leq \Delta_3(\beta, c_1) = \frac{(2+\beta)(1-c_1)}{4+3\beta}$, and (ii) $\frac{\partial |MR_2|}{\partial \theta} > 0$ for all feasible θ when $\Delta > \Delta_3(\beta, c_1)$. The expression for $\theta_3(\beta, \Delta, c_1)$ is provided in the Appendix.

We summarize these results next.

Proposition 3 (Asymmetric Firms):

1. *When the asymmetry in starting costs between firms is small, an increase in competitive intensity raises the marginal return from cost reduction in less competitive markets but lowers it in more competitive markets for both firms.*

2. *When the asymmetry in starting costs between firms is large, an increase in competitive intensity monotonically increases the marginal return from cost reduction for the stronger firm but monotonically decreases it for the weaker firm.*

As in the symmetric case, an increase in competitive intensity affects each firm's marginal return to cost reduction through two opposing effects: an increased sales gain from the cost-induced price cut (as demand becomes more elastic) versus a decreased price-cost margin gain (due to compression in markups). Therefore, when initial cost asymmetry is small, the symmetric-case logic continues to apply and marginal returns remain non-monotonic with respect to competitive intensity.

With large initial cost asymmetry, however, the comparative statics diverge qualitatively between the two firms. For the lower-cost (stronger) firm, its cost reduction strengthens its cost advantage over its rival. As competitive intensity increases, market shares become more sensitive to relative costs and the price cut by the stronger firm attracts a disproportionately large sales expansion. This sales gain effect outweighs the price-margin compression effect and therefore the marginal returns to cost reduction for the stronger firm increases monotonically with competitive intensity. For the higher-cost (weaker) firm, a cost reduction partially narrows its cost disadvantage and results in lowering its price. However, with higher competitive intensity, this price reduction serves mainly to defend its shrinking market share rather than generate sufficient incremental sales. At the same time, stronger competition compresses its already thin markups, and therefore the price margin compression effect dominates. Thus, the weaker firm's marginal return to cost reduction falls monotonically with competitive intensity.

■ **Social Welfare.** For asymmetric firms in a duopoly, social welfare is given by

$$SW = \frac{1}{8}\left(4(1-c_i-c_j) + (2+\beta)(c_i^2+c_j^2) - 2\beta c_i c_j - \frac{4(1+\beta)^3(c_i-c_j)^2}{(4+\beta(3-\theta))^2} - \frac{4(2-c_i-c_j)^2}{(4+\beta(1-\theta))^2}\right).$$

The effect on social welfare in response to a unit change in firm i's cost c_i is:

$$\frac{\partial SW}{\partial c_i} = \frac{1}{8}\left(-4(1-c_i) + 2b(c_i-c_j) - \frac{8(1+\beta)^3(c_i-c_j)}{(4+\beta(3-\theta))^2} - \frac{8(-2+c_i+c_j)}{(4+\beta(1-\theta))^2}\right).$$

We derive the following result in the Appendix

Proposition 4 (Social Welfare for Asymmetric Firms): (i) *Cost reduction of the stronger firm increases social welfare and this welfare gain increases monotonically with competition.* (ii) *Cost reduction of the weaker firm can increase or decrease social welfare, and this welfare change is non-monotonic in competitive intensity.*

Intuitively, a cost reduction for the stronger (lower-cost) firm both lowers production costs and shifts output towards the efficient firm – both of which help increase social welfare. As competition intensity increases, the shift in demand to the stronger firm is larger thus resulting in greater social welfare gain from cost reduction with higher competitive intensity.

On the other hand, a cost reduction for the weaker (higher-cost) firm has two opposing welfare effects: it lowers production costs, but it also reallocates demand towards the inefficient firm. When the cost gap is small, this reallocation loss is limited while stronger competition increases pass-through and consumption gain in response to the lower cost. Therefore, the welfare gain from lowering the cost increases in this case. When the cost gap is intermediate, the reallocation loss is stronger. As competition gets more intense, the incremental output expansion from the cost cut is limited as the weaker firm's pass through serves mainly to defend loss of market share. The welfare gain here decreases with the increase in competitive intensity. Finally, when the cost gap is large, the reallocation loss is so high that cost reduction of the weaker firm is welfare reducing. Stronger competition makes market shares more sensitive to relative costs and prices, resulting in higher pass-through and more demand shift to the weaker firm. This amplifies the reallocation loss and thus the welfare loss increases with increase in competitive intensity.

5. Conclusion

Reducing costs is a central strategic objective for firms, influencing decisions on process redesign, technology adoption, and outsourcing. We examined how the intensity of price competition, as captured by the conjectural-variation parameter, shapes firms' marginal private benefits from reducing per-unit variable costs in a differentiated-products framework. We showed that for symmetric firms, these returns are non-monotonic in competitive intensity; however, when firms differ significantly in their starting per-unit costs, then these relationships can become monotonic.

Appendix

1. $\theta_1(\beta) = \frac{1}{6\beta^2(\beta+2)}\left(4X_1 + \frac{4\beta^2(15\beta(\beta+2)+16)}{X_1} + 2\beta(3\beta(\beta+6)+16)\right)$, where

$X_1 = (3\sqrt{3}\sqrt{\beta^8(\beta+1)^2(\beta+2)^2(27\beta(\beta+2)+28)} - \beta^3(9\beta(\beta+2)(3\beta(\beta+2)+10)+64))^{1/3}$.

2.(i) $\theta_n(\beta) = Root[F_n(\theta,\beta,n);1]$ (notation: $Root[k(x);i]$ is the ith exact root of polynomial $k(x)=0$ in Mathematica), where $F_n(\theta,\beta,n) = (\beta^3n^3 - 3\beta^3n^2 + 3\beta^3n - \beta^3 + \beta^2n^3 - 2\beta^2n^2 + \beta^2n)\theta^3 + (-3\beta^3n^3 + 9\beta^3n^2 - 9\beta^3n + 3\beta^3 - 7\beta^2n^3 + 12\beta^2n^2 - 5\beta^2n - 4\beta n^3 + 4\beta n^2)\theta^2 + (3\beta^3n^3 - 9\beta^3n^2 + 9\beta^3n - 3\beta^3 + 10\beta^2n^3 - 16\beta^2n^2 + 7\beta^2n + 11\beta n^3 - 7\beta n^2 + 4n^3)\theta - \beta^3n^3 + 3\beta^3n^2 - 3\beta^3n + \beta^3 - 4\beta^2n^3 + 6\beta^2n^2 - 3\beta^2n - 5\beta n^3 + 3\beta n^2 - 2n^3$.

(ii) $\frac{\partial|MR_i|}{\partial n} = \frac{2(c-1)\Psi(\beta,n,\theta)}{(n-1)n^3(1+S(\theta))^3(1+\beta+S(\theta))^2}$, where $\Psi(\beta,n,\theta) = (1+\beta)n^2S(\theta)(1+S(\theta))^2(1+\beta+S(\theta)) + n((1+\beta)^2 - (1+\beta)^2S(\theta) - 5(\beta+1)^2S(\theta)^2 - (3+\beta(3\beta+8))S(\theta)^3 - 2\beta S(\theta)^4) + \beta S(\theta)(2\beta(-1+S(\theta)(2+S(\theta))) + (S(\theta)+1)(S(\theta)(S(\theta)+5)-2))$ and $S(\theta) = 1 + \frac{\beta(1-\theta)(n-1)}{n}$.

3. $\Delta_2(\beta,c_1) = \frac{1}{6(\beta+2)}\left(-\frac{4\sqrt[3]{2}(\beta^2+12\beta+12)(1-c_1)^2}{\sqrt[3]{X_2}} + 2(\beta+6)(1-c_1) + 2^{2/3}\sqrt[3]{X_2}\right)$, where

$X_2 = 7\beta^3c_1 - 21\beta^3c_1^2 + 21\beta^3c_1 - 7\beta^3 - 36\beta^2c_1^3 + 108\beta^2c_1^2 - 108\beta^2c_1 + 36\beta^2 - 36\beta c_1^3 + 108\beta c_1^2 - 108\beta c_1 + 36\beta + ((7\beta^3c_1^3 - 21\beta^3c_1^2 + 21\beta^3c_1 - 7\beta^3 - 36\beta^2c_1^3 + 108\beta^2c_1^2 - 108\beta^2c_1 + 36\beta^2 - 36\beta c_1^3 + 108\beta c_1^2 - 108\beta c_1 + 36\beta)^2 + 4(3(\beta+2)(\beta c_1^2 - 2\beta c_1 + \beta + 10c_1^2 - 20c_1 + 10) - (\beta c_1 - \beta + 6c_1 - 6)^2)^3)^{1/2}$.

4. $\theta_2(\beta,\Delta,c_1) = Root[F_2(\theta,\beta,\Delta,c_1);1]$, where

$F_2(\theta,\beta,\Delta,c_1) = (\beta^5\Delta - 2\beta^4c_1 + 2\beta^4\Delta + 2\beta^4 - 4\beta^3c_1 + 4\beta^3)\theta^4 + (-2\beta^5\Delta + 12\beta^4c_1 - 16\beta^4\Delta - 12\beta^4 + 56\beta^3c_1 - 16\beta^3\Delta - 56\beta^3 + 48\beta^2c_1 - 48\beta^2)\theta^3 + (-24\beta^4c_1 + 12\beta^4\Delta + 24\beta^4 - 192\beta^3c_1 + 36\beta^3\Delta + 192\beta^3 - 360\beta^2c_1 + 24\beta^2\Delta + 360\beta^2 - 192\beta c_1 + 192\beta)\theta^2 + (2\beta^5\Delta + 20\beta^4c_1 + 16\beta^4\Delta - 20\beta^4 + 232\beta^3c_1 + 80\beta^3\Delta - 232\beta^3 + 656\beta^2c_1 + 128\beta^2\Delta - 656\beta^2 + 704\beta c_1 + 64\beta\Delta - 704\beta + 256c_1 - 256)\theta - \beta^5\Delta - 6\beta^4c_1 - 14\beta^4\Delta + 6\beta^4 - 92\beta^3c_1 - 100\beta^3\Delta + 92\beta^3 - 280\beta^2c_1 - 280\beta^2\Delta + 280\beta^2 - 320\beta c_1 - 320\beta\Delta + 320\beta - 128c_1 - 128\Delta + 128$.

5. $\theta_3(\beta,\Delta,c_1) = Root[F_3(\theta,\beta,\Delta,c_1);1]$ for $\Delta < Min\left\{\frac{2(1-c_1)}{\beta+2}, \Delta_2(\beta,c_1)\right\}$, and

$Root[F_3(\theta,\beta,\Delta,c_1);2]$ for $\frac{2(1-c_1)}{\beta+2} < \Delta < \Delta_2(\beta,c_1)$,where

$F_3(\theta,\beta,\Delta,c_1) = (\beta^5\Delta + 2\beta^4c_1 + 4\beta^4\Delta - 2\beta^4 + 4\beta^3c_1 + 4\beta^3\Delta - 4\beta^3)\theta^4 + (-2\beta^5\Delta - 12\beta^4c_1 - 28\beta^4\Delta + 12\beta^4 - 56\beta^3c_1 - 72\beta^3\Delta + 56\beta^3 - 48\beta^2c_1 - 48\beta^2\Delta + 48\beta^2)\theta^3 + (24\beta^4c_1 + 36\beta^4\Delta - 24\beta^4 + 192\beta^3c_1 + 228\beta^3\Delta - 192\beta^3 + 360\beta^2c_1 + 384\beta^2\Delta - 360\beta^2 + 192\beta c_1 + 192\beta\Delta - 192\beta)\theta^2 + (2\beta^5\Delta - 20\beta^4c_1 - 4\beta^4\Delta + 20\beta^4 - 232\beta^3c_1 - 152\beta^3\Delta + 232\beta^3 - 656\beta^2c_1 - 528\beta^2\Delta + 656\beta^2 - 704\beta c_1 - 640\beta\Delta + 704\beta - 256c_1 - 256\Delta + 256)\theta - \beta^5\Delta + 6\beta^4c_1 - 8\beta^4\Delta - 6\beta^4 + 92\beta^3c_1 - 8\beta^3\Delta - 92\beta^3 + 280\beta^2c_1 - 280\beta^2 + 320\beta c_1 - 320\beta + 128c_1 - 128$.

6. $\frac{\partial SW}{\partial c_1} = (c_1-1) + \frac{\Delta}{2} - \frac{2(-2+2c_1+\Delta)}{(4+\beta(1-\theta))^2} < 0$ and $\frac{\partial}{\partial\theta}|\frac{\partial SW}{\partial c_1}| = \frac{4\beta(-2+2c_1+\Delta)}{(4+\beta(1-\theta))^3} < 0$ within the feasibility zone $0 < c_1 < 1$ and $\Delta < \overline{\Delta}_1(\beta)$ defined in the text.

$\frac{\partial SW}{\partial c_2} = \frac{1}{4}[-2 + 2c_1 + (2+\beta)\Delta - \frac{4(1+\beta)^3\Delta}{(4+\beta(3-\theta))^2} - \frac{4(-2+2c_1+\Delta)}{(4+\beta(1-\theta))^2}] < 0$ when $\Delta < \Delta_{S0}$ and ≥ 0 when $\Delta_{S0} \leq \Delta < \overline{\Delta}_1(\beta)$, where

$$\Delta_{S0} = \frac{2(1-c_1)(-4-3\beta+\beta\theta)^2(-6-\beta+\beta\theta)}{\beta^4\theta^3 - 7\beta^4\theta^2 + 11\beta^4\theta - 5\beta^4 + 2\beta^3\theta^3 - 28\beta^3\theta^2 + 86\beta^3\theta - 60\beta^3 - 28\beta^2\theta^2 + 192\beta^2\theta - 252\beta^2 + 128\beta\theta - 384\beta - 192}.$$

$\frac{\partial}{\partial\theta}|\frac{\partial SW}{\partial c_2}| = \frac{2\beta(1+\beta)^3\Delta}{(4+\beta(3-\theta))^3} + \frac{2\beta(-2+2c_1+\Delta)}{(4+\beta(1-\theta))^3}$ when $\Delta < \Delta_{S0}$ and $-\frac{2\beta(1+\beta)^3\Delta}{(4+\beta(3-\theta))^3} - \frac{2\beta(-2+2c_1+\Delta)}{(4+\beta(1-\theta))^3}$ when $\Delta_{S0} \leq \Delta < \overline{\Delta}_1(\beta)$. It follows that $\frac{\partial}{\partial\theta}|\frac{\partial SW}{\partial c_2}| < 0$ when $\Delta < \Delta_{S1}$, $\frac{\partial}{\partial\theta}|\frac{\partial SW}{\partial c_2}| \geq 0$ when $\Delta_{S1} \leq \Delta < \Delta_{S0}$, and $\frac{\partial}{\partial\theta}|\frac{\partial SW}{\partial c_2}| < 0$ when $\Delta_{S0} \leq \Delta < \overline{\Delta}_1(\beta)$, where

$$\Delta_{S1} = \frac{2(1-c_1)(\beta\theta-3\beta-4)^3}{(\beta^2\theta-\beta^2+2\beta\theta-8\beta-8)(\beta^4\theta^2-2\beta^4\theta+\beta^4+\beta^3\theta^2-8\beta^3\theta+7\beta^3+\beta^2\theta^2-12\beta^2\theta+23\beta^2-8\beta\theta+32\beta+16)}.$$

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