Operational, Economic and Policy Design Issues in Beekeeping and Honey Industry in India

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ABSTRACT

Apiculture is the practice of bee-*keeping* for products and services – such as honey, beeswax, pollen, bee venom, propolis, royal jelly, and pollination, etc. – under *natural* ecosystems on a large scale. World over, *farmers* adopt beekeeping as a primary (farming) activity or an additional income-generating option. An estimated 90 million honey bee colonies produced around 1.9 million tons of honey globally in 2020. More than 12 million honey bee colonies were functional for bee farming in India in 2020, producing around 0.07 million tons of honey.

While beekeeping is ecologically and economically beneficial, it faces severe challenges due to inefficient management practices adopted by farmers and policymakers. For instance, poor migratory practices, poor management of colony and bee boxes, product adulteration, lower awareness about product quality, poor quality norms and standards, etc., have adversely impacted the productivity of the entire beekeeping sector in India. In this thesis, we adopt a systematic approach to address operational, economic, and policy issues critical to enhancing beekeeping's productivity.

Capacity Building Through Migration: In commercial beekeeping, migration refers to the temporary relocation of bee boxes to places having suitable flora to sustain beehives and increase bee strength and colony productivity. One of the critical features of migration is that the productivity of beekeeping in subsequent seasons depends on the efficiency of the *current* season's migratory practices. However, the cost of migration, inefficient colony management, and poor migratory practices typically offset the said advantages. In our first study, we develop an inter-temporal analytical model and address the challenges in migratory beekeeping operations by characterizing the associated stochastic settings. We investigate whether it is profitable for a beekeeper to

migrate bee boxes and provide insights into how a *small* beekeeper's strategy is distinct from that of a *large* beekeeper. Our model would provide guidelines for beekeepers to enhance the efficiency of beekeeping by adopting appropriate migration strategies.

Designing Market Participation Strategy: Beekeeping can potentially improve the livelihood of marginal farmers and economically weaker classes. Firms engage economically weaker classes in joint-value production of scarce varieties of honey and associated value-added products and serve the product to the poor and the affording consumers. While most such firms have exhibited impressive growth over time, their growth trajectory gets dampened due to limited supply capacity and resource constraints. Appropriately managing the trade-offs between serving the poor and enhancing profitability by providing suitable value-added products to consumers in urban markets often benefit the firm in the long run. Using a product line design framework in our second study, we capture the associated trade-offs and obtain insights into efficient profit generation and capacity allocation strategies. Our model would be helpful to firms in improving their profitability by efficiently designing product lines and serving the bottom of the pyramid.

Policy-making Under Quality Alteration: Quality alteration refers to the artificial modification of product characteristics to attain economic benefits. In food products, such as honey, quality alteration results in the consumption of *low*-quality products by consumers that are particularly unaware of appropriate product quality norms. In our third study, we develop a game-theoretic model to characterize the implications of quality norms designed by policymakers and the response strategies firms adopt. Our approach is based on the social cost minimization theory, where policymakers do not maximize social welfare but rather alleviate the worst-case performance. With the explicit consideration of social cost due to quality alteration, we show that as the consumer's willingness to pay for the supply quality increases, quality alteration reduces when policy standards are relaxed and vice versa. We also show that welfare-maximizing policymakers always prefer a stringent policy norm which may induce firms to excessively process the honey, thereby reducing its medicinal value and usefulness. Our study would provide a framework for policymakers that restraints firms from selling low-quality honey without quality alteration, thereby improving the industry's performance.

In this thesis, we address three prominent issues in this sector: production, market participation, and policy design. The results of our studies can be helpful to all the stakeholders in the beekeeping sector, specifically government and policymakers, farmers, commercial beekeepers, for-profit firms, non-governmental organizations (NGOs), and other allied industries that directly or indirectly depend upon beekeeping products.

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How artificial intelligence and technological advancement will transform humankind might be debatable, but the future of our planet unarguably depends on bees and natural pollinators. It is natural to ponder why and how so? Albert Einstein, one of the greatest physicists of all time, stated, "we would have no more than four years to live if bees disappear from the surface of the earth."

In our dissertation, our objective was two-fold. Firstly, we tried to understand and highlight the critical operational and supply chain issues in the beekeeping and honey industries that were ignored in the operations literature. Secondly, we tried to address this sector's three prominent issues: production, market participation, and policy design.

In our first study, we looked at the production and capacity-building strategy and decisions by the farmers and commercial beekeepers through the migration of bee boxes. We considered stochasticity in productivity and provided insights into the optimal decision-making strategies of the farmers and beekeepers. We also captured and analyzed the risk averseness of the farmers and beekeepers in our study.

In our second study, we tried to address firm-level issues. In beekeeping, firms usually train marginal farmers and create awareness about the positive benefits of beekeeping along with farming. Through this, they create a network society of beekeepers and simultaneously improve supply capacity and profitability by involving them in co-production. Therefore, we addressed market participation challenges from the perspective of such firms. We considered product quality perception of high-quality products served by the firm to the high-value consumers and supply capacity limitations. We provided meaningful insights on the optimal strategies adopted by the firm to enhance its profitability by serving the product to the afforded and low-value consumers.

Our third study looked at the critical issue of quality alteration prevalent in the food industries, specifically the honey industry. We tried to address the macro level issue of voluntary quality alteration by the firms and policy level implications of it. We developed a game-theoretic model to characterize the implications of quality norms designed by policymakers and the response strategies adopted by firms.

The results of our studies can be advantageous to all the stakeholders in the beekeeping sector, specifically government and policymakers, farmers, commercial beekeepers, for-profit firms, non-governmental organizations (NGOs), and other allied industries that directly or indirectly depend upon beekeeping products.

We briefly summarize the relevance of our studies for the key stakeholders. The governments and policymakers can use significant insights obtained in each study through policy interventions: (i) to improve the farmers' income, which is aligned with the government's vision to double the farmers' income by the year 2023, (ii) to provide a consistent source of livelihood to the tribal and marginal farmers, (iii) to prevent quality alteration of honey by the firms that can severely impact consumers health, and (iv) to monitor and launch several schemes and initiatives which can have a beneficial impact on beekeeping sector.

Firms can use our insights: (i) to improve yield by establishing joint-production-based honey supply chains, (ii) to improve product quality through technological interventions such as traceability, (iii) to enhance their profitability by improving product perception and supply capacity through joint-value production by engaging marginal and poor farmers, and (iv) to overall invest in commercial beekeepers and alleviate the overall operations and supply chain issues.

Commercial beekeepers can use insights from our thesis to enhance their profitability and productivity. NGOs and other farming welfare societies can use our insights to engage the bottom of the pyramid in co-production. Other allied sectors and firms, such as cosmetics, hospitality, horticulture, etc., that indirectly depend upon beekeeping may also benefit from the insights. In the following section 5.1, we present the future directions and scope of our work.

5.1 Future Research

Though we tried to address critical challenges in the beekeeping sector in our dissertation, significant unaddressed challenges lay the foundation as opportunities for future research. We mention a few of them as follows:

We observed from our field study that the precise mapping of the floral resource is necessary for migratory beekeeping. Obsolete floral mapping charts provided by the government agencies associated with beekeeping need re-mapping. A suitable migratory route needs to be scheduled with the help of appropriate operations research techniques such as heuristics and routing models.

Though pollination is beneficial for higher farm production, which can address the food shortage issue, beekeepers in India are reluctant to consider pollination services. On the other hand, the government, through its strategic policies such as the 'sweet revolution,' focuses on higher honey production, and beekeepers stress the bees for multiple honey extractions. Therefore, not only does the quality of honey decline, but bees' strength also reduces. While honey production improves farmers' income and migration improves bee productivity, pollination improves farm production. Therefore, there is a clear trade-off between pollination, honey production, and migration, which we take up as future research to design policies that can resolve the trade-offs and improve the beekeeping sector.

Government agencies and policymakers must focus on many serious problems, such as quality adulteration. Most firms and beekeepers alter the honey quality for economic gains. However, the real problem arises when a firm voluntarily alters the honey quality (e.g., improves the perceived quality) when it receives altered or poor-quality honey from the producers. Similarly, few beekeepers voluntarily alter the honey quality (e.g., dilute the honey with fructose syrup) to match with other beekeepers as the price for the honey is known in the wholesale market. Therefore, a firm's action of quality alteration induces farmers and beekeepers to alter the quality of raw honey supplied. As the honey production process is inter-temporal, the other players' actions in the previous cycle determine the quality output realized in the current cycle. We observe an inherent repeated moral hazard issue among the producers. Therefore a suitable mechanism must be developed to prevent quality adulteration and improve the supply chain.

We also observed from our field study that beekeepers and budding entrepreneurs in commercial beekeeping could not create a market for by-products such as beeswax, pollen, propolis, and bee venom. Various industries, such as cosmetics, depend upon bee wax as a primary constituent in their products. Similarly, pollens are rich sources of proteins, but the lack of market significantly decreases the value proposition of such by-products.

Climate change is real, and crops, together with birds, bees, and other farm-friendly insects, are adapting to climate change. However, understanding the magnitude of the adaptation globally needs researchers' attention. It is not incorrect to link bee colony collapse to climate change and productivity losses. We can address such issues that will benefit beekeeping and other similar sectors.

As we discuss these critical challenges, many other significant issues still need to be identified. We can systematically address all these operational, economic, and policy issues in beekeeping to lay the foundation of solid business opportunities in the beekeeping sector and improve the income of all beekeepers and farmers.

Appendix A

Proofs of Study 1

A.1 Proofs of Proposition

Proof. Proof of Proposition 2.1.

From (2.1), it is noted that the beekeeper's objective function is concave in x_s, and the optimization problem $\max_{x_s \geq 0}$ is a convex program. The KKT first order condition (FOC) is necessary and sufficient to demonstrate optimality of a solution. The KKT FOC is described as $\partial \pi_2 / \partial x_s = 0$, suggesting that $x_s = k_\beta x_m + x_1 - \dfrac{\theta}{2c_o}$ satisfies the FOC condition. The constraint $x_s \geq 0$ implies that $x_s^*(x_m)$ as described in (2.4) is indeed optimal. □

A.2 Theorem 1

Proof. Proof of Theorem 2.1. From (2.5), it is noted that the beekeeper's objective function is concave in x_m, and the optimization problem $\max_{x_m \geq 0}$ is a convex program. The KKT first order condition (FOC) is necessary and sufficient to demonstrate optimality of a solution. Solving for Scenario 1 and 2 and then comparing the results:

A.2.1 Scenario 1

$x_m \geq \underline{x_m}$: P_1^b : $max_{x_m \geq 0}\ \pi_1(x_m, x_s^*(x_m); x_1)$, s.t. (i) $\underline{x_m} \leq x_m \leq x_1$, (ii) $0 \leq \underline{x_m} \leq x_1$ when $x_s^*(x_m) = (k_\beta x_m + x_1) - \dfrac{\theta}{2c_o}$. The KKT FOC is described as $\partial \pi_1 / \partial x_m = 0$ suggesting that $\widehat{x_m} = \dfrac{\delta k_\beta p_{b_1} - p_1 + 2c_o x_1}{2(c_o + c_m)}$ satisfies the FOC condition for (2.5.2.1).

The constraint from (2.5.2.1) gives the bounds on x_1 defined as follows:

$$
\begin{aligned}
x_{11} &= \frac{\theta\ (c_o + c_m)\ -\ c_o\ k_\beta\ (\delta k_\beta\ p_{b_1}\ -\ p_1)}{2c_o(\beta c_o\ +\ c_m)}; \qquad & x_{12} &= \frac{\delta k_\beta\ p_{b_1}\ -\ p_1}{2c_m};\\
x_{13} &= \frac{p_1\ -\ \delta k_\beta\ p_{b_1}}{2c_o}; & x_{14} &= \frac{\theta}{2c_o};\\
x_{15} &= \frac{\theta}{2\beta c_o}.
\end{aligned}
\tag{A.1}
$$

A.2.2 Scenario 2

$x_m < \underline{x_m}$: P_1^b : $max_{x_m \geq 0}\ \pi_1(x_m, x_s^*(x_m); x_1)$, s.t. (i) $0 \leq x_m \leq \underline{x_m}$, (ii) $x_m \leq x_1$, (iii) $\underline{x_m} \geq 0$ when $x_s^*(x_m) = 0$. The KKT FOC is described as $\partial \pi_1 / \partial x_m = 0$ suggesting that $\widetilde{x_m} = \dfrac{(\delta k_\beta p_2 - p_1) + 2c_o x_1 (1 - \delta k_\beta)}{2(\delta k_\beta^2 c_o + c_o + c_m)}$ satisfies the FOC condition for (2.5.2.2). The constraint from (2.5.2.2) gives the bounds on x_1 defined as follows:

$$
\begin{aligned}
x_{21} &= \frac{\theta(\delta k_\beta^2 c_o + c_o + c_m) - c_o k_\beta (\delta k_\beta p_2 - p_1)}{2c_o(\beta c_o + c_m)}; \quad & x_{22} &= \frac{\delta k_\beta\ p_2\ -\ p_1}{2\ (\delta k_\beta \beta c_o\ +\ c_m)};\\
x_{23} &= \frac{p_1\ -\ \delta k_\beta\ p_2}{2\ (\delta k_\beta \beta c_o\ +\ c_m)}; & x_{24} &= x_{14}
\end{aligned}
\tag{A.2}
$$

We obtain Theorem 2.1 on comparing these two scenario's in terms of migration and box selling strategy. □

A.3 Proposition 2

Proof. Proof of Proposition 2.2. On comparing the x_{ij} from scenario 1 and scenario 2 we get bounds on δ defined as follows:

$$\begin{aligned}
\delta_{11} &= \frac{p_1-\theta}{k_\beta p_{b_1}}; & \delta_{12} &= \frac{p_1-(\theta/\beta)}{k_\beta p_{b_1}}; & \delta_{13} &= \frac{p_1}{k_\beta p_{b_1}};\\
\delta_{14} &= \frac{p_1+(\theta c_m)/(\beta c_o)}{k_\beta p_{b_1}}; & \delta_{15} &= \frac{p_1\ +(\theta c_m)/(c_o)}{k_\beta p_{b_1}}; & \delta_{21} &= \frac{p_1}{k_\beta p_2};\\
\delta_{22} &= \frac{p_1\ +(\theta c_m)/(c_o)}{k_\beta p_{b_1}-k_\beta^2\theta}; & \delta_{23} &= \frac{\beta p_1-\theta}{k_\beta(\beta p_2-\theta)}
\end{aligned} \tag{A.3}$$

Comparing all x_{ij} and simplifying, we obtain the following results:

i. $x_{11}-x_{13}\geq 0 \implies (\theta+\delta k_\beta p_{b_1}-p_1)\geq 0$, which holds true for, $\delta\geq\delta_{11}$

ii. $x_{14}-x_{11}\geq 0 \implies (\theta+\delta k_\beta p_{b_1}-p_1)\geq 0$, which holds true for, $\delta\geq\delta_{11}$

iii. $x_{12}-x_{11}\geq 0 \implies \dfrac{\theta c_m}{\beta c_o}+p_1\leq\delta k_\beta p_{b_1}$,which holds true for, $\delta\geq\delta_{14}$. Similarly $x_{15}-x_{11}\geq 0$ true for $\delta\geq\delta_{14}$

iv. $x_{14}-x_{13}\geq 0 \implies (\theta+\delta k_\beta p_{b_1}-p_1)\geq 0$, which holds true for, $\delta\geq\delta_{11}$. Also $x_{15}\leq x_{14}$ for all δ.

v. $x_{12}-x_{14}\geq 0 \implies \dfrac{\theta c_m}{c_o}+p_1\leq\delta k_\beta p_{b_1}$, which holds true for, $\delta\geq\delta_{15}$.

vi. $x_{12}-x_{15}\geq 0 \implies \dfrac{\theta c_m}{\beta c_o}+p_1\leq\delta k_\beta p_{b_1}$, which holds true for, $\delta\geq\delta_{14}$.

vii. $x_{12}-x_{13}\geq 0 \implies \delta k_\beta p_{b_1}\geq p_1$, which holds true for $\delta\geq\delta_{13}$

viii. $x_{15}-x_{13}\geq 0 \implies \delta k_\beta\beta p_{b_1}\geq\beta p_1-\theta$, which holds true for $\delta\geq\delta_{12}$

ix. $x_{21}-x_{23}\geq 0 \implies (\theta+\delta k_\beta p_{b_1}-p_1)\geq 0$, holds true for $\delta\geq\delta_{11}$.

x. $x_{22}-x_{23}\geq 0 \implies (\delta k_\beta p_2-p_1)\geq 0$, holds true for $\delta\geq\delta_{21}$.

xi. $x_{21} - x_{22} \geq 0 \implies \dfrac{\theta c_m}{\beta c_o} + p_1 \leq \delta k_\beta p_{b_1}$, which holds true for, $\delta \leq \delta_{14}$.

xii. $x_{21} - x_{14} \geq 0 \implies (\theta + \delta k_\beta p_{b_1} - p_1) \geq 0$, holds true for $\delta \geq \delta_{11}$. Similarly $x_{14} - x_{23} \geq 0$ true for $\delta \geq \delta_{11}$.

xiii. $x_{21} - x_{14} \geq 0 \implies \dfrac{p_1}{k_\beta p_{b_1} - k_\beta^2 \theta} + \dfrac{\theta c_m}{c_o(k_\beta p_{b_1} - k_\beta^2 \theta)} \geq 0$, holds true for $\delta \geq \delta_{22}$.

xiv. $x_{11} - x_{21} = 0$, therefore, $x_{21} = x_{11}$.

xv. $x_{21} - x_{12} \geq 0 \implies \dfrac{\theta c_m}{\beta c_o} + p_1 \leq \delta k_\beta p_{b_1}$, which holds true for, $\delta \leq \delta_{14}$. Similar result holds for $x_{21} - x_{12} \geq 0$.

xvi. $x_{21} - x_{13} \geq 0$, holds true for $\delta \geq \delta_{11}$. Same results holds for $x_{13} - x_{23} \geq 0$ and $x_{11} - x_{23} \geq 0$.

xvii. $x_{12} - x_{23} \geq 0 \implies \delta k_\beta p_{b_1} \geq p_1$, which holds true for $\delta \geq \delta_{13}$

xviii. $x_{15} - x_{23} \geq 0 \implies \dfrac{\theta(1 - \delta k_\beta) - \beta p_1 + \delta k_\beta \beta p_2}{2 c_o \beta (1 - \delta k_\beta)}$, which on simplification, holds true for $\delta \geq \delta_{23}$

In order to sequence δ_{ij} we compare each δ from both the scenarios:

i. $\delta_{12} - \delta_{11} = \dfrac{\theta}{\beta p_b 1} \implies \geq 0$

ii. $\delta_{21} - \delta_{12} = \dfrac{\theta(p_2 - \beta p_1)}{k_\beta} \implies \geq 0 \quad if \ \beta \leq \dfrac{p_2}{p_1}$

iii. $\delta_{12} - \delta_{23}$, here since numerator of both are equal, simply comparing denominator we get $k_\beta(\beta p_2 - \theta) - \beta k_\beta p_{b_1} = k_\beta^2 \theta \implies \delta_{12} \geq \delta_{23}$

iv. $\delta_{23} - \delta_{11} = \dfrac{k_\beta(p_{b_1} - p_1) + \theta}{k_\beta p_{b_1}(k_\beta(\beta p_2 - \theta))} \implies \geq 0$

v. $\delta_{14} - \delta_{13} = \dfrac{\theta c_m}{\beta k_\beta c_o p_{b_1}} \implies \geq 0$

vi. $\delta_{15} - \delta_{14} = \dfrac{\theta c_m}{\beta p_{b_1} c_o} \implies \geq 0$

vii. $\delta_{22} - \delta_{15} = \dfrac{k_\beta^2 \theta(p_1 c_o + \theta c_m)}{c_o} \implies \geq 0$

viii. $\delta_{13} - \delta_{11} = \dfrac{\theta}{k_\beta p_{b_1}} \implies \geq 0$

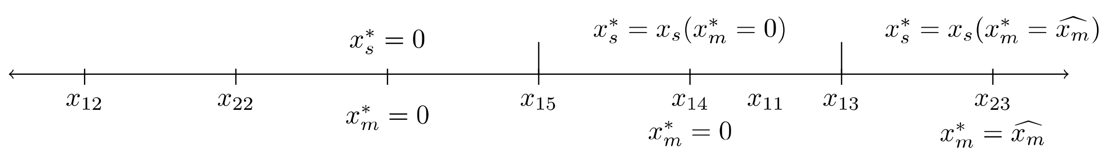
Hence, we get two sequences of δ_{ij} on the basis of β:

- $\delta_{11} \leq \delta_{23} \leq \delta_{12} \leq \delta_{21} \leq \delta_{13} \leq \delta_{14} \leq \delta_{15} \leq \delta_{22} \quad if \beta \leq \dfrac{p_2}{p_1}$
- $\delta_{11} \leq \delta_{23} \leq \delta_{21} \leq \delta_{12} \leq \delta_{13} \leq \delta_{14} \leq \delta_{15} \leq \delta_{22} \quad otherwise.$

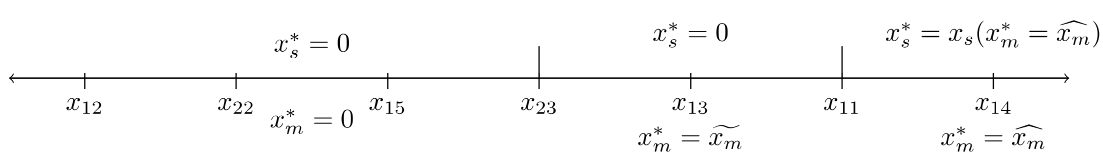
□

Evaluating all possible strategies for the beekeeper based on δ_{ij} and x_{ij} and using Theorem 2.1 (considering sequence 1 of δ_{ij}, when $\beta \leq \frac{p_2}{p_1}$).

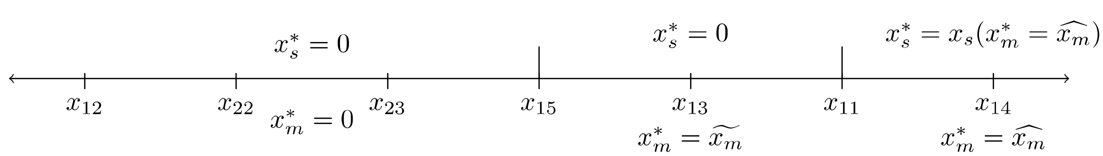
i. For $\delta < \delta_{11}$:



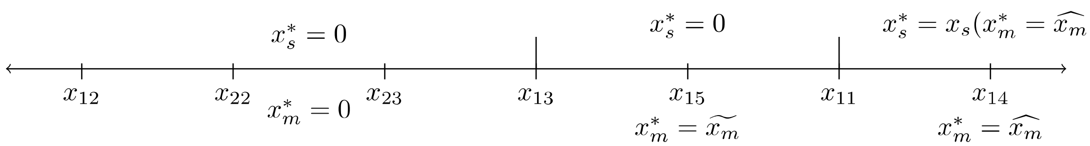
ii. For $\delta_{11} \leq \delta < \delta_{23}$:



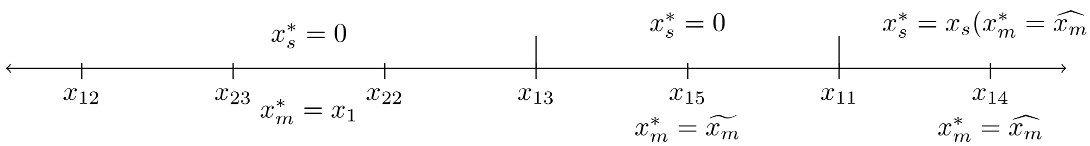
iii. For $\delta_{23} \leq \delta < \delta_{12}$:



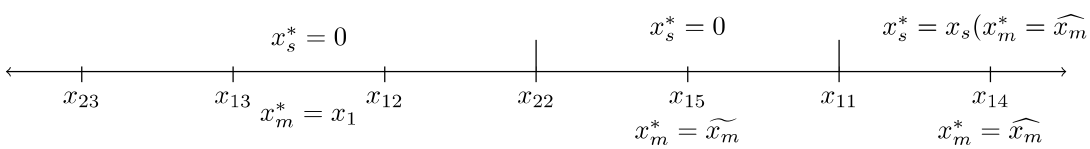
iv. For $\delta_{12} \leq \delta < \delta_{21}$:



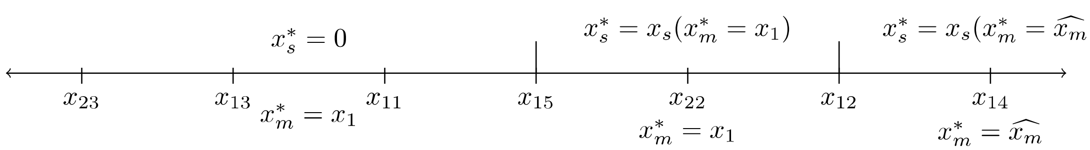
v. For $\delta_{21} \leq \delta < \delta_{13}$:



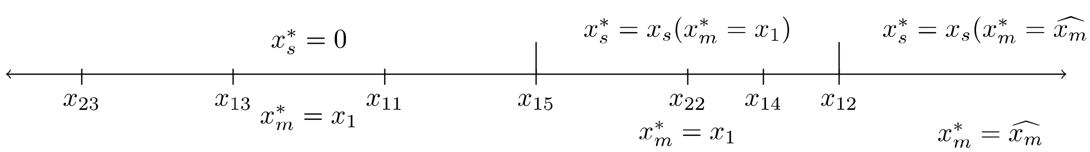
vi. For $\delta_{13} \leq \delta < \delta_{14}$:



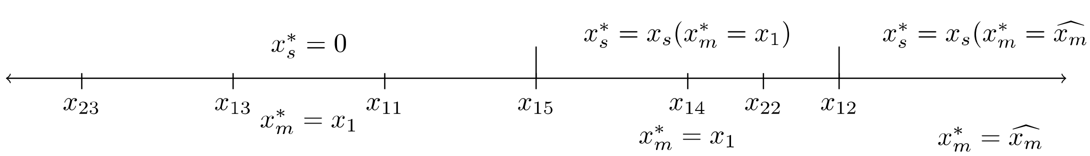
vii. For $\delta_{14} \leq \delta < \delta_{15}$:



viii. For $\delta_{15} \leq \delta < \delta_{22}$:

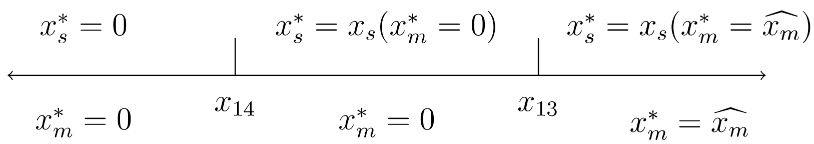


ix. For $\delta_2 \leq \delta < \min\{\frac{1}{k_\beta}, 1\}$:

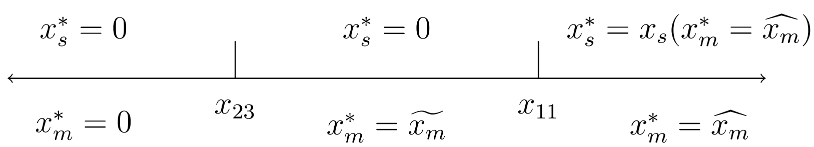


We get the similar results from the sequence of δ_{ij}, when $\beta > \frac{p_2}{p_1}$. From above comparisons, we observe and define unique optimal solutions as follows:

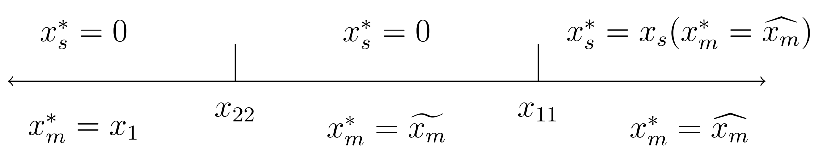
i. For $\delta < \delta_{11}$:



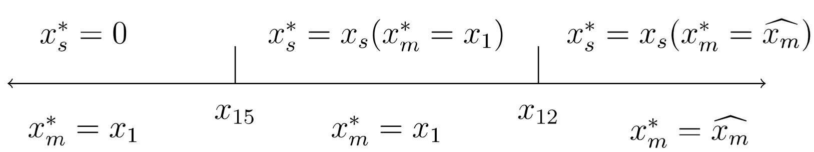
ii. For $\delta_{11} \leq \delta < \delta_{21}$:



iii. For $\delta_{21} \leq \delta < \delta_{14}$:



iv. For $\delta_{14} \leq \delta < \min\{\frac{1}{k_\beta}, 1\}$:



This proves our Proposition 2.2. □

A.4 Proposition 3

Proof. Proof of Proposition 2.3.

Since there is no change in the profit function of beekeeper in period 2 under uncertainty, from (2.1), we note that the beekeeper's objective function is concave in

x_s, and the optimization problem $\max_{x_s \geq 0}$ is a convex program. The KKT first order condition (FOC) is necessary and sufficient to demonstrate optimality of a solution. The KKT FOC is described as $\partial \pi_2 / \partial x_s = 0$, suggesting that $x_s = k_\beta x_m + x_1 - \frac{\theta}{2c_o}$, where $\beta \in (\beta_l, \beta_h)$ satisfies the FOC condition. The constraint $x_s \geq 0$ gives the thresholds $\underline{x_m^{\beta_h}}$ *and* $\underline{x_m^{\beta_h}}$, and implies that $x_s^{*u}(x_m)$ as described in (2.13) is indeed optimal. □

A.5 Theorem 2

Proof. Proof of Theorem 2.2. From (2.16), it is noted that the beekeeper's objective function is concave in x_m, and the optimization problem $\max_{x_m \geq 0}$ is a convex program. The KKT first order condition (FOC) is necessary and sufficient to demonstrate optimality of a solution. Solving for Scenario 1, 2 and 3 as obtained from Proposition 2.3 and then comparing the results:

A.5.1 Scenario 1

When $x_m \geq \underline{x_m^{\beta_l}}$: The beekeeper sells the box in both, low and high pollen content. The beekeeper's problem in period 1 is:

$$\begin{aligned} P_{1u}^b : \max_{x_m \geq 0} \ \mathbb{E}\Big(\pi_1^u(x_m, x_s^*(x_m, \beta_{l,h}) \Big) &= \nu \Big(\pi_1(x_m(\beta_l)) + \delta \pi_2(x_s^*(x_m, \beta_l) \Big) \\ &+ (1-\nu) \Big(\pi_1(x_m(\beta_h)) + \delta \pi_2(x_s^*(x_m, \beta_h) \Big) \end{aligned} \tag{A.4}$$

s.t. (i) $x_m \geq \underline{x_m^{\beta_l}}$, (ii) $x_m \leq x_1$, (iii) $\underline{x_m^{\beta_h}} \geq 0$, (iv) $\underline{x_m^{\beta_l}} \leq x_1$, and (v) $x_m \geq 0$.

The KKT FOC is described as $\partial \pi_1^u / \partial x_m = 0$ suggesting that $\widehat{x_m^u} = \dfrac{\delta \mathbb{E}(k_\beta) p_{b_1} - p_1 + 2c_o x_1}{2(c_o + c_m)}$ satisfies the FOC condition for beekeeper's first period problem in scenario 1.

where $\mathbb{E}(k_\beta) = \nu k_{\beta_l} + (1-\nu)k_{\beta_h}$. The constraint from (A.4) gives the bounds on x^u_{ij} defined as follows:

$$
\begin{aligned}
x^u_{11} &= \frac{\theta\ (c_o + c_m)\ -\ c_o\ k_{\beta_l}\ (\delta\mathbb{E}(k_\beta)\ p_{b_1}\ -\ p_1)}{2c_o(\beta_l c_o\ + c_m)}; \quad & x^u_{12} &= \frac{\delta\mathbb{E}(k_\beta)\ p_{b_1}\ -\ p_1}{2c_m};\\
x^u_{13} &= \frac{p_1\ -\ \delta\mathbb{E}(k_\beta)\ p_{b_1}}{2c_o}; & x^u_{14} &= \frac{\theta}{2c_o};\\
x^u_{15} &= \frac{\theta}{2\beta_l c_o};
\end{aligned}
\tag{A.5}
$$

A.5.2 Scenario 2

When $\underline{x^{\beta_h}_m} < x_m \le \underline{x^{\beta_l}_m}$: The beekeeper sells the box only when high pollen content is realized and does not sell when low pollen content is realized. The beekeeper's problem in period 1 is:

$$
\begin{aligned}
P^b_{1u} : \max_{x_m \ge 0}\ \mathbb{E}\Bigg(\pi^u_1(x_m, x^*_s(x_m, \beta_{l,h})\Bigg) &= \nu\Bigg(\pi_1(x_m(\beta_l)) + \delta\pi_2(x^*_s = 0)\Bigg)\\
&+(1-\nu)\Bigg(\pi_1(x_m(\beta_h)) + \delta\pi_2(x^*_s(x_m, \beta_h)\Bigg)
\end{aligned}
\tag{A.6}
$$

s.t. (i) $\underline{x^{\beta_h}_m} \le x_m \le \underline{x^{\beta_l}_m}$, (ii) $x_m \le x_1$, (iii) $\underline{x^{\beta_h}_m} \ge 0$, (iv) $\underline{x^{\beta_h}_m} \le x_1$, and (v) $x_m \ge 0$.

The KKT FOC is described as $\partial\pi^u_1/\partial x_m = 0$ suggesting that $\widetilde{x^u_m} = \dfrac{\delta(\nu k_{\beta_l}\ p_2\ + (1-\nu)k_{\beta_h} p_{b_1}) -\ p_1\ + 2c_o x_1(1-\nu\delta k_{\beta_l})}{2\ (\nu\delta k_{\beta_l}\beta_l c_o\ + c_o\ + c_m)}$ satisfies the FOC condition for beekeeper's first period problem in scenario 2.

The constraint from (A.6) gives the bounds on x_{ij}^u defined as follows:

$$\begin{aligned}
x_{22}^u &= \frac{\theta\ (c_o + c_m + \delta c_o \mathbb{E}(k_\beta^2))\ -\ c_o\ k_{\beta_h}\ (\delta \mathbb{E}(k_\beta)\ p_2\ -\ p_1)}{2c_o(\beta_h c_o\ + c_m\ - \nu\delta c_o k_{\beta_l}(k_{\beta_h}\ - k_{\beta_l}))}; \\
x_{23}^u &= \frac{\delta(\nu k_{\beta_l}\ p_2\ + (1-\nu)k_{\beta_h} p_{b_1}) -\ p_1}{2\ (\nu\delta k_{\beta_l}\beta_l c_o\ +\ c_m)}; \\
x_{24}^u &= \frac{p_1 - \delta(\nu k_{\beta_l}\ p_2\ + (1-\nu)k_{\beta_h} p_{b_1})}{2c_o(1-\nu\delta k_\beta^2)}; \\
x_{14}^u &= \frac{\theta}{2c_o}; \\
x_{25}^u &= \frac{\theta}{2c_o\beta_h}; \quad \text{where } x_{21}^u = x_{11}^u
\end{aligned} \tag{A.7}$$

A.5.3 Scenario 3

When $x_m \leq \underline{x_m^{\beta_h}}$: The beekeeper does not sell boxes in both high and low types of pollen content. The beekeeper's problem in period 1 is:

$$\begin{aligned}
P_{1u}^b : \max_{x_m \geq 0}\ \mathbb{E}\Bigg(\pi_1^u(x_m, x_s^*(x_m, \beta_{l,h})\Bigg) &= \nu\Bigg(\pi_1(x_m(\beta_l)) + \delta\pi_2(x_s^* = 0\Bigg) \\
&+ (1-\nu)\Bigg(\pi_1(x_m(\beta_h)) + \delta\pi_2(x_s^* = 0\Bigg)
\end{aligned} \tag{A.8}$$

s.t. (i) $x_m \leq \underline{x_m^{\beta_h}}$, (ii) $x_m \leq x_1$, (iii) $\underline{x_m^{\beta_h}} \geq 0$, and (iv) $x_m \geq 0$.

The KKT FOC is described as $\partial\pi_1^u/\partial x_m = 0$ suggesting that $\widehat{\widehat{x_m^u}} = \dfrac{\delta\mathbb{E}(k_\beta)p_2\ - p_1\ + 2c_o x_1(1-\delta\mathbb{E}(k_\beta))}{2\ (\delta c_o\mathbb{E}(k_\beta^2)\ + c_o\ + c_m)}$ satisfies the FOC condition for beekeeper's first period problem in scenario 3.

The constraint from (A.8) gives the bounds on x_{ij}^u defined as follows:

$$x_{31}^u = x_{22}^u; \quad x_{32}^u = \frac{\delta p_2 \mathbb{E}(k_\beta)\ - p_1}{2(c_m + \delta c_o \mathbb{E}(k_\beta))}; \quad x_{33}^u = \frac{p_1 - \delta p_2 \mathbb{E}(k_\beta)}{2c_o(1-\delta\mathbb{E}(k_\beta))}; \quad x_{14}^u = \frac{\theta}{2c_o} \tag{A.9}$$

We obtain Theorem 2.2 on comparing these three scenario's in terms of migration and box selling strategy under uncertainty. □

A.6 Proposition 4

Proof. Proof of Proposition 2.4. On comparing the x_{ij} in scenario 1, 2 and 3, we get the bounds on δ defined as follows:

Comparing all x_{ij}, simplifying and defining δ_{ij^u} for comparison and sequencing, we obtain the following results:

i. $x_{11}^u - x_{13}^u \geq 0 \implies (\theta + \delta\mathbb{E}(k_\beta)p_{b_1} - p_1) \geq 0$, which holds true for, $\delta \geq \delta_{11}^u$. Similar condition holds true for $x_{14}^u - x_{11}^u \geq 0$, $x_{14}^u - x_{13}^u \geq 0$.

ii. $x_{15}^u - x_{13} \geq 0 \implies \theta - \beta_l p_1 + \delta p_{b_1}\beta\mathbb{E}(k_\beta) \geq 0$, which holds true for $\delta \geq \delta_{12}^u$.

iii. $x_{12}^u - x_{11}^u \geq 0 \implies p_1\beta_l c_o + \theta c_m \geq \delta p_{b_1} c_o \beta_l \mathbb{E}(k_\beta)$, which holds true for $\delta \geq \delta_{14}^u$. Similar condition holds true for $x_{15}^u - x_{11}^u \geq 0$, and $x_{15}^u - x_{12}^u \geq 0$, $x_{21}^u - x_{23}^u \geq 0$.

iv. $x_{12}^u - x_{13}^u \geq 0 \implies \delta p_{b_1} c_o \mathbb{E}(k_\beta) \geq p_1$, which holds true for $\delta \geq \delta_{13}^u$.

v. $x_{14}^u - x_{15}^u \geq 0$ for all values of β and δ. Similarly $x_{14}^u - x_{25}^u \geq 0$ holds true always.

vi. $x_{12}^u - x_{14}^u \geq 0 \implies \theta c_m - \delta p_{b_1} c_o \mathbb{E}(k_\beta) + p_1 c_o \leq 0$, which holds true for $\delta \geq \delta_{15}^u$.

vii. $x_{21}^u - x_{24}^u \geq 0 \implies (\theta + \delta\mathbb{E}(k_\beta)p_{b_1} - p_1) \geq 0$, which holds true for $\delta \geq \delta_{11}^u$. Similar results hold true for $x_{21}^u - x_{14}^u \geq 0$, $x_{14}^u - x_{24}^u \geq 0$, $x_{21}^u - x_{22}^u \geq 0$, $x_{22}^u - x_{24}^u \geq 0$, $x_{22}^u - x_{24}^u \geq 0$, $x_{31}^u - x_{33}^u \geq 0$, $x_{31}^u - x_{34}^u \geq 0$, and $x_{14}^u - x_{33}^u \geq 0$.

viii. $x_{25}^u - x_{24}^u \geq 0 \implies \big(\delta(p_{b_1}\mathbb{E}(k_\beta) + k_{\beta_h}(\nu k_{\beta_l} p_2 + (1-\nu)k_{\beta_h} p_{b_1})\big) \geq\ p_1\beta_h - \theta$, which is true for $\delta \geq \delta_{21}^u$.

ix. $x_{23}^u - x_{24}^u \geq 0 \implies \delta(\nu k_{\beta_l} p_2 + (1-\nu)k_{\beta_h} p_{b_1})(c_o + c_m + \delta\nu k_{\beta_{l^2}} c_o) \geq 0$, ignoring the negative root, this condition holds true for $\delta \geq \delta_{22}^u$.

x. $x^u_{21} - x^u_{25} \geq 0 \implies (\delta p_{b_1}\mathbb{E}(k_\beta) - p_1))c_o k_{\beta_l}\beta_h \geq (\theta c_o(k_{\beta_h} - k_{\beta_l}) + \theta c_m k_{\beta_h}$, which holds true for the condition $\delta \geq \delta^u_{24}$.

xi. $x^u_{23} - x^u_{14} \geq 0 \implies \delta\big(\mathbb{E}(k_\beta)\ p_{b_1} - \nu k^2_{\beta_l}\theta\big) \geq p_1 c_o + \theta c_m$, which holds true for $\delta \geq \delta^u_{25}$.

xii. $x^u_{23} - x^u_{25} \geq 0 \implies \delta\big(\mathbb{E}(k_\beta\beta) + \nu p_2 k_{\beta_l}(k_{\beta_h} - k_{\beta_l})\big) \geq p_1\beta_h + \dfrac{\theta c_m}{c_o}$, which holds true for $\delta \geq \delta^u_{23}$. Similar result holds true for $x^u_{23} - x^u_{25} \geq 0$, $x^u_{25} - x^u_{22} \geq 0$, and $x^u_{31} - x^u_{32} \geq 0$.

xiii. $x^u_{32} - x^u_{33} \geq 0 \implies (\delta p_2\mathbb{E}(k_\beta) - p_1) \geq 0$, which holds true for $\delta \geq \delta^u_{31}$.

xiv. $x^u_{14} - x^u_{32} \geq 0 \implies \delta\big(\mathbb{E}(k_\beta\beta)p_{b_1} - p_2\mathbb{E}(k^2_\beta)\big) \geq p_1 + \dfrac{\theta c_m}{c_o}$, which holds true for $\delta \geq \delta^u_{32}$.

Based on above comparisons, we define the bounds of δ_{ij} as follows:

$$
\begin{aligned}
\delta^u_{11} &= \frac{p_1 - \ \theta}{\mathbb{E}(k_\beta)\ p_{b_1}}; &
\delta^u_{12} &= \frac{p_1 - \ (\theta/\beta_l)}{\mathbb{E}(k_\beta)\ p_{b_1}}; \\
\delta^u_{13} &= \frac{p_1}{\mathbb{E}(k_\beta)\ p_{b_1}}; &
\delta^u_{14} &= \frac{p_1 + (\dfrac{\theta c_m}{\beta_l c_o})}{\mathbb{E}(k_\beta)\ p_{b_1}}; \\
\delta^u_{15} &= \frac{p_1 + (\dfrac{\theta c_m}{c_o})}{\mathbb{E}(k_\beta)\ p_{b_1}}; &
\delta^u_{21} &= \frac{p_1\beta_h - \theta}{p_{b_1}\mathbb{E}(k_\beta) + k_{\beta_h}(\nu k_{\beta_l}p_2 + (1-\nu)k_{\beta_h}p_{b_1})}; \\
\delta^u_{22} &= \frac{p_1}{\nu k_{\beta_l}p_2 + (1-\nu)k_{\beta_h}p_{b_1}}; &
\delta^u_{23} &= \frac{p_1\beta_h \ + \theta(c_m/c_o)}{p_{b_1}\mathbb{E}(k_\beta\beta) + \nu p_2 k_{\beta_l}(k_{\beta_h} - k_{\beta_l})}; \\
\delta^u_{24} &= \frac{p_1 + \big(\dfrac{\theta c_o(k_{\beta_h} - k_{\beta_l}\big) + \theta c_m k_{\beta_h}}{c_o k_{\beta_l}\beta_h})}{p_{b1}\mathbb{E}(k_\beta)}; &
\delta^u_{25} &= \frac{p_1 + (\dfrac{\theta c_m}{c_o})}{\mathbb{E}(k_\beta)\ p_{b_1} - \nu k^2_{\beta_l}\theta}; \\
\delta^u_{31} &= \frac{p_1}{\mathbb{E}(k_\beta)\ p_2}; &
\delta^u_{32} &= \frac{p_1 \ + (\theta c_m)/(c_o)}{\mathbb{E}(k_\beta\beta)p_{b_1} - p_2\mathbb{E}(k^2_\beta)}
\end{aligned}
\tag{A.10}
$$

In order to sequence δ_{ij^u}, we compare each δ defined in (A.10).

i. We observe that, $\delta^u_{11} \leq \delta^u_{12} \leq \delta^u_{13} \leq \delta^u_{14} \leq \delta^u_{15} \leq \delta^u_{24}$. Also, $\delta^u_{31} \leq \delta^u_{13}$.

ii. We observe that, $\delta^u_{23} \leq \delta^u_{14}$. Also, $\delta^u_{23} \leq \delta^u_{25}$ and $\delta^u_{21} \leq \delta^u_{22} \leq \delta^u_{32}$.

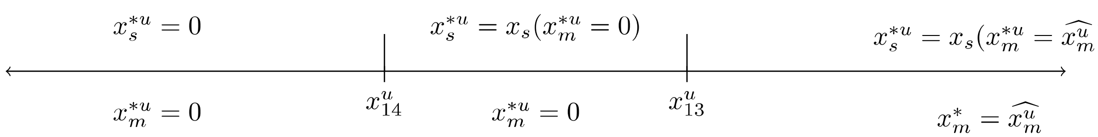
iii. $\delta^u_{13} - \delta^u_{22} = \dfrac{\nu\theta k_{\beta_l}}{\mathbb{E}(k_\beta)p_{b_1}(\nu k_{\beta_l}p_2 + (1-\nu)k_{\beta_h}p_{b_1})} \implies \geq 0$, therefore $\delta^u_{22} \leq \delta^u_{13}$. Similarly $\delta^u_{32} \leq \delta^u_{24}$.

Based on comparisons the sequence of δ_{ij} is describe as follows:

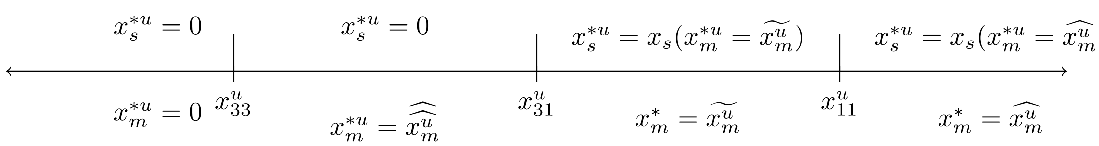
- $\delta^u_{11} \leq \delta^u_{12} \leq \delta^u_{21} \leq \delta^u_{31} \leq \delta^u_{22} \leq \delta^u_{13} \leq \delta^u_{23} \leq \delta^u_{14} \leq \delta^u_{15} \leq \delta^u_{25} \leq \delta^u_{32} \leq \delta^u_{24}$

Evaluating all possible strategies for the beekeeper based on δ^u_{ij} and x^u_{ij} and using Theorem 2.2. Simplifying as in A.3 we obtain as follows:

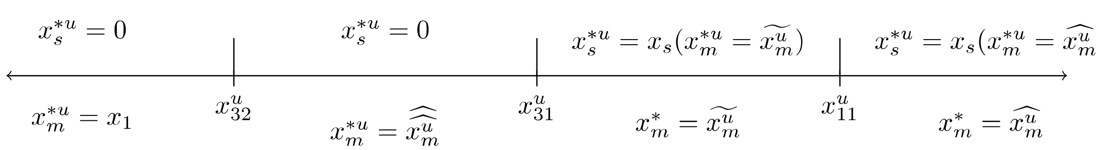
i. For $\delta < \delta^u_{11}$:



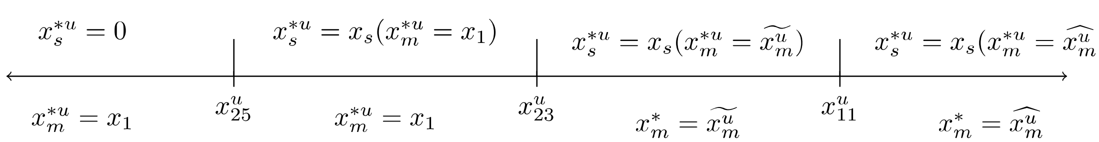
ii. For $\delta^u_{11} \leq \delta < \delta^u_{31}$:



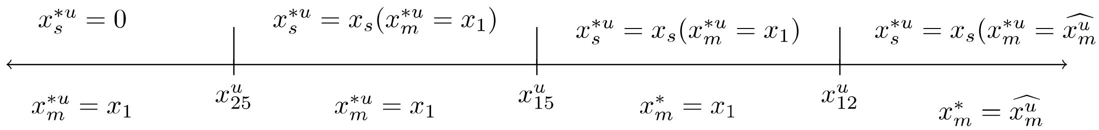
iii. For $\delta^u_{31} \leq \delta < \delta^u_{23}$:



iv. For $\delta^u_{23} \leq \delta < \delta^u_{14}$:



v. For $\delta^u_{14} \leq \delta < \min\{1, \dfrac{1}{\mathbb{E}(k_\beta)}\}$:

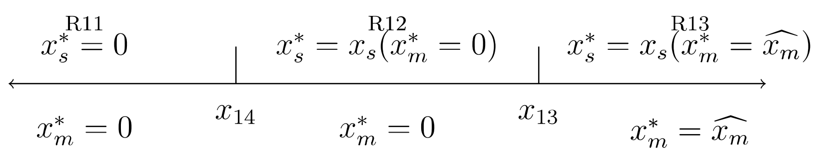


This proves our Proposition 2.4. □

A.7 Theorem 3

Proof. Proof of Theorem 2.3. From the results of Proposition 2.2, (i) we solve beekeeper's optimization problem described in (2.21) in each scenario, (ii) obtain each region's optimal solution, and (iv) compare it with the constraints in each region to obtain thresholds to describe the optimal number of bee boxes. For brevity we write the proof of first scenario, other proofs are derived similarly.

i. For $\delta < \delta_{11}$:



1 The beekeeper's problem in R11 (region 1 scenario 1) is described as:

$$
\begin{aligned}
P_{1o}^b:\ & \max_{x_1 \geq 0}\big(\pi_1(x_m^*(x_1) = 0, x_s^*(x_1) = 0)\big) \\
\text{s.t.} \quad & \text{(i) } x_1 \leq x_{14}, \text{ (ii) } \delta \leq \delta_{11}, \text{ (iii) } x_1 \geq 0
\end{aligned}
$$

2 The beekeeper's problem in R12 (region 2 scenario 1) is described as:

$$
\begin{aligned}
P_{1o}^b:\ & \max_{x_1 \geq 0}\big(\pi_1(x_m^*(x_1) = 0,\ x_s^*(x_1) = x_s(x_m^*(x_1) = 0)\big) \\
\text{s.t.} \quad & \text{(i) } x_{14} < x_1 \leq x_{13},\ \text{ (ii) } \delta \leq \delta_{11},\ \text{ (iii) } x_1 \geq 0
\end{aligned}
$$

3 The beekeeper's problem in R13 (region 3 scenario 1) is described as:

$$P^b_{1o}: \max_{x_1 \geq 0} \Big(\pi_1(x^*_m(x_1) = \widehat{x_m}, x^*_s(x_1) = x_s(x^*_m(x_1) = \widehat{x_m})\Big)$$
$$\text{s.t.} \qquad \text{(i) } x_1 \geq x_{13}, \text{ (ii) } \delta \leq \delta_{11}, \text{ (iii) } x_1 \geq 0$$

We observe that the beekeeper's objective function in each region is concave in x_1 and the optimization problem $max_{x_1 \geq 0}$ is a convex program. From the KKT FOC which is described as $\partial \pi^b_{1o}(x_1)/\partial x_1 = 0$, we obtain $\widehat{x^1_1} = \dfrac{\delta p_2 - c_b + p_1}{2c_o(1+\delta)}$, $\widehat{x^2_1} = \dfrac{p_1 - c_b + \delta p_{b_1}}{2c_o}$, and $\widehat{x^3_1} = \dfrac{c_m p_1 + \delta p_{b_1}(\beta c_o + c_m) - c_b(c_o + c_m)}{2c_o c_m}$ respectively. Similarly $\widehat{x^4_1}$, $\widehat{x^5_1}$, *and* $\widehat{x^6_1}$ are obtained from solving optimization problems in scenario 2, 3 and 4. The constraints from each region in each scenario gives the bounds on δ^{sk}_j described as follows:

$$\begin{aligned}
\delta^{s1}_1 &= \frac{c_b}{\beta p_{b_1}}; & \delta^{s1}_2 &= \frac{\theta + c_b - p_1}{p_{b_1}}; \\
\delta^{s1}_3 &= \frac{c_b - p_1}{p_2}; & \delta^{s2}_1 &= \frac{\theta c_m + c_b(\beta c_o + c_m) - c_m p_1}{p_{b_1}(\beta^2 c_o + c_m)}; \\
\delta^{s2}_2 &= \frac{c_b}{k_\beta c_b + \beta(p_2 - p_1)}; & \delta^{s3}_1 &= \frac{c_m(c_b - p_1)}{c_m p_2 + \beta c_o(\beta p_1 - k_\beta c_b)}; \\
\delta^{s3}_2 &= \frac{c_b}{\beta p_2}; & \delta^{s4}_1 &= \frac{c_b - p_1}{p_{b_1}}; \\
\delta^{s4}_2 &= \frac{\theta c_m + \beta c_o c_b}{\beta^2 c_o p_{b_1}}; & \delta_{11} &= \frac{p_1 - \theta}{k_\beta p_{b_1}}; \\
\delta_{12} &= \frac{p_1 - (\theta/\beta)}{k_\beta p_{b_1}}; & \delta_{21} &= \frac{p_1}{k_\beta p_2}
\end{aligned} \tag{A.11}$$

Comparing all δ^{sk}_j, simplifying and defining p^j_1 from the comparison and sequencing, we obtain the following results:

i. $\delta_{11} - \delta^{s1}_1 \geq 0 \implies k_\beta c_b \leq \beta p_1 - \beta\theta$, which holds true for $p_1 \geq p^1_1$. Similar result holds true for $\delta_{11} - \delta^{s1}_2 \geq 0$, $\delta^{s1}_1 - \delta^{s1}_2 \geq 0$, $\delta^{s2}_1 - \delta_{11} \geq 0$, $\delta^{s2}_2 - \delta_{11} \geq 0$, $\delta^{s2}_2 - \delta^{s2}_1 \geq 0$.

ii. $\delta_2^{s1} - \delta_3^{s1} \geq 0 \implies p_2 + c_b \geq p_1$, which holds true for $p_1 \leq p_1^2$.

iii. $\delta_1^{s2} - \delta_{21} \geq 0 \implies \big(k_\beta p_2(\theta c_m + (\beta c_o + c_m)c_b)\big) \leq p_{b_1}(\beta^2 c_o + c_m) + p_2 k_\beta c_m$, which holds true for $p_1 \leq p_1^3$. Similar result holds true for $\delta_1^{s3} - \delta_{21} \geq 0$

iv. $\delta_2^{s2} - \delta_{21} \geq 0 \implies (k_\beta c_b) \leq p_1 \beta$, which holds true for $p_1 \leq p_1^4$. Similar results holds true for $\delta_2^{s2} - \delta_3^{s1} \geq 0$, $\delta_1^{s3} - \delta_{21} \geq 0$.

v. $\delta_3^{s1} - \delta_{11} \geq 0 \implies k_\beta p_{b_1} c_b + p_2 \theta \leq p_1(k_\beta p_{b_1} + p_2)$, which holds true for $p_1 \leq p_1^5$.

vi. $\delta_{14} - \delta_1^{s2} \geq 0 \implies (\beta c_o + c_m)(k_\beta \beta c_o c_b - c_m \theta) \leq \beta^2 c_o p_1(\beta c_o + c_m)$, which holds true for $p_1 \geq p_1^6$. Similar results holds true for $\delta_{14} - \delta_1^{s4} \geq 0$, $\delta_{14} - \delta_2^{s4} \geq 0$

vii. $\delta_{14} - \delta_2^{s3} \geq 0 \implies k_\beta c_o c_b p_{b_1]} \leq \beta c_o p_2 p_1 + p_2 \theta c_m$, which hold true for $p_1 \geq p_1^7$.

viii. $\delta_1^{s1} - \delta_3^{s1} \geq 0 \implies \beta p_{b_1} p_1 \geq c_b k_\beta p_{b_1} - c_b \theta$, which implies $p_1 \geq p_1^8$.

ix. $\delta_1^{s2} - \delta_3^{s1} \geq 0 \implies p_1 \geq \dfrac{c_b p_{b_1}(\beta^2 c_o + c_m) - c_b p_2(\beta c_o + c_m) - p_2 \theta c_m}{p_{b_1}(\beta^2 c_o + c_m) - p_2 c_m}$, which implies $p_1 \geq p_1^9$.

x. $\delta_1^{s3} - \delta_1^{s1} \geq 0 \implies p_1 \leq \dfrac{c_b k_\beta(c_m p_{b_1} + \beta c_b) - c_b c_o \theta}{\beta(\beta c_o c_b + c_m p_{b_1})}$, which implies $p_1 \leq p_1^{10}$.

xi. $\delta_2^{s4} - \delta_2^{s1} \geq 0 \implies p_1 \leq \beta^2 c_o p_1 \geq k_\beta \beta c_o c_b + \beta^2 c_o \theta - \theta c_m$, which implies $p_1 \geq p_1^{11}$.

xii. $\delta_1^{s4} - \delta_3^{s1} \geq 0 \implies \beta^2 c_o p_{b_1} p_1 \geq k_\beta \beta c_o c_b p_{b_1} - \beta c_o c_b \theta - \theta c_m p_2$, which implies $p_1 \geq p_1^{12}$.

xiii. $\delta_1^{s2} - \delta_2^{s3} \geq 0 \implies \beta\theta(\beta c_o c_b + p_2 c_m) + c_b c_m(k_\beta p_2 + \theta \geq \beta c_m p_2 p_1$, which implies $p_1 \leq p_1^{13}$.

xiv. $\delta_2^{s2} - \delta_2^{s4} \geq 0 \implies \beta(\theta c_m + \beta c_o c_b) \geq k_\beta c_b(\theta c_m + \beta c_o c_b) + \beta\theta(p_2 c_m + \beta c_o c_b)$, which implies $p_1 \geq p_1^{14}$.

xv. $\delta_1^{s2} - \delta_2^{s4} \geq 0 \implies c_b(k_\beta \beta^2 c_o^2 c_b + \beta^2 c_o c_m p_{b_1}) - c_m p_2(\theta c_m + \beta c_o c_b) \geq \beta p_1\big(\beta^2 c_o^2 c_b + \beta c_o c_m p_{b_1}\big)$, which implies $p_1 \leq p_1^{15}$.

xvi. $\delta_2^{s3} - \delta_3^{s1} \geq 0 \implies \beta p_2 p_1 \geq k_\beta p_2 c_b + c_b\theta$, which implies $p_1 \geq p_1^{16}$.

Based on above comparisons we describe p_1^j as follows:

$$p_1^1 = \frac{k_\beta c_b + \beta\theta}{\beta}; \qquad p_1^2 = (p_2 + c_b);$$

$$p_1^3 = \frac{k_\beta p_2\big(\theta c_m + (\beta c_o + c_m)c_b\big)}{p_{b_1}(\beta^2 c_o + c_m) + p_2 k_\beta c_m}; \qquad p_1^4 = \frac{k_\beta c_b}{\beta};$$

$$p_1^5 = \frac{k_\beta p_{b_1} c_b + p_2\theta}{\beta}; \qquad p_1^6 = \frac{\beta k_\beta c_o c_b - \ c_m\theta}{\beta^2 \ c_o};$$

$$p_1^7 = \frac{k_\beta p_{b_1} c_o c_b - \ p_2 c_m \theta}{\beta p_2 c_o}; \qquad p_1^8 = \frac{c_b(k_\beta p_{b_1} - \theta)}{\beta p_{b_1}};$$

$$p_1^9 = \frac{c_b p_{b_1}(\beta^2 c_o + c_m) - c_b p_2(\beta c_o + c_m) - p_2\theta c_m}{p_{b_1}(\beta^2 c_o + c_m) - p_2 c_m}; \quad p_1^{10} = \frac{c_b k_\beta(c_m p_{b_1} + \beta c_b) - c_b c_o\theta}{\beta(\beta c_o c_b + c_m p_{b_1})};$$

$$p_1^{11} = \frac{\beta c_o(k_\beta c_b + \beta\theta) - \theta c_m}{\beta^2 c_o}; \qquad p_1^{12} = \Big(\frac{c_b(k_\beta p_{b_1} - \theta)}{\beta p_{b_1}}\Big) - \Big(\frac{\theta c_m p_2}{\beta^2 c_o p_{b_1}}\Big);$$

$$p_1^{13} = \frac{\beta\theta(\beta c_o c_b + p_2 c_m) + c_b c_m(k_\beta p_2 + \theta)}{\beta c_m p_2};$$

$$p_1^{14} = \frac{k_\beta c_b(\theta c_m + \beta c_o c_b) + \beta\theta(p_2 c_m + \beta c_o c_b)}{\beta(\theta c_m + \beta c_o c_b)};$$

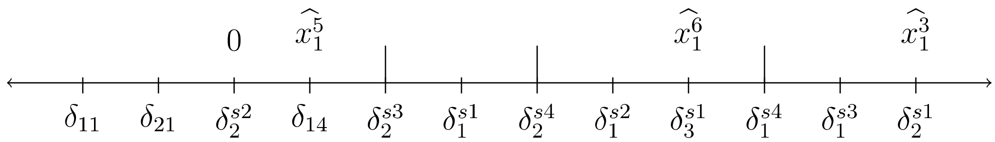
$$p_1^{15} = \frac{c_b(p_{b_1} c_m + k_\beta c_o c_b)}{(p_{b_1} c_m + \beta c_o c_b)} - \frac{c_m p_2(\theta c_m + \beta c_o c_b)}{\beta^2 c_o(p_{b_1} c_m + \beta c_o c_b)}; \qquad p_1^{16} = \frac{c_b(k_\beta p_2 + \theta)}{\beta p_2} \tag{A.12}$$

This proves Theorem 2.3. □

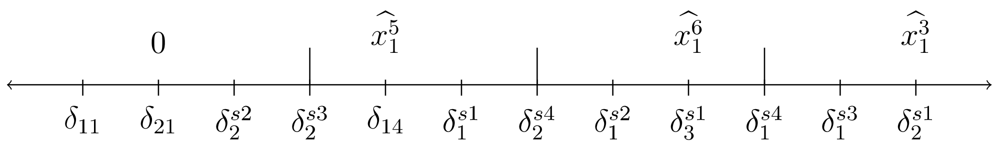
A.8 Proposition 5

Proof. Proof of Proposition 2.5. On comparing and sequencing p_1^j obtained from Theorem 2.3 we evaluate all possible optimal size regions for the beekeeper and define as follows:

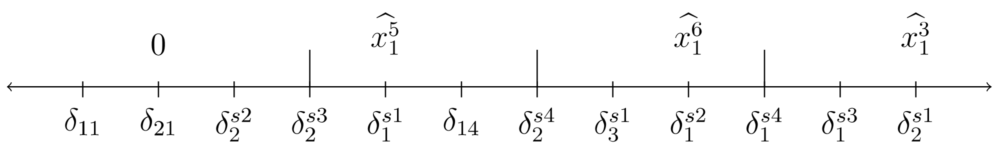
i. For $p_1 < p_1^7$:



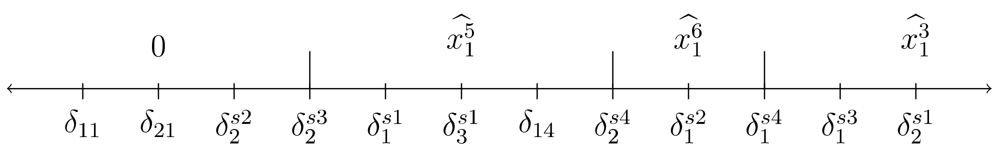
ii. For $p_1^7 \leq p_1 < p_1^9$:



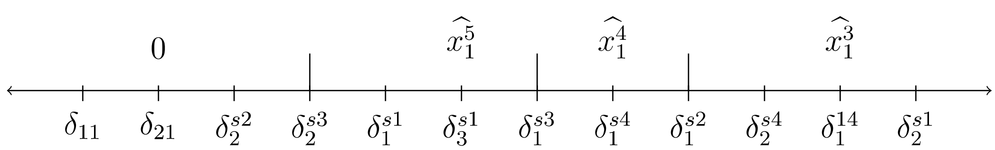
iii. For $p_1^9 \leq p_1 < p_1^{12}$:



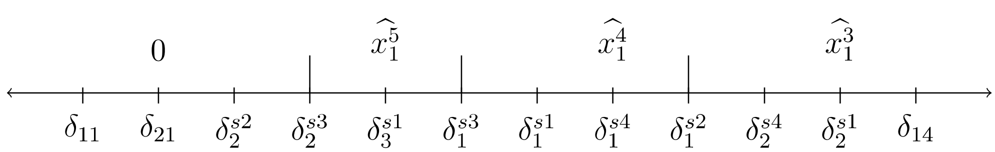
iv. For $p_1^{12} \leq p_1 < p_1^6$:



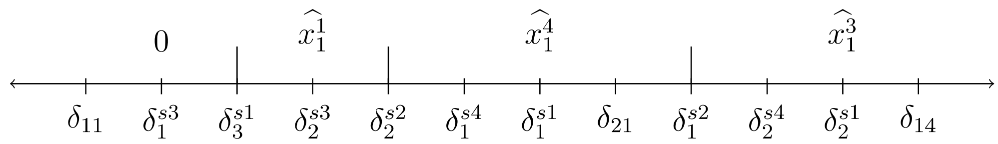
v. For $p_1^6 \leq p_1 < p_1^8$:



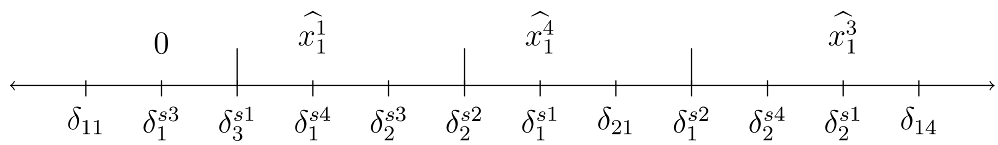
vi. For $p_1^8 \leq p_1 < p_1^4$:



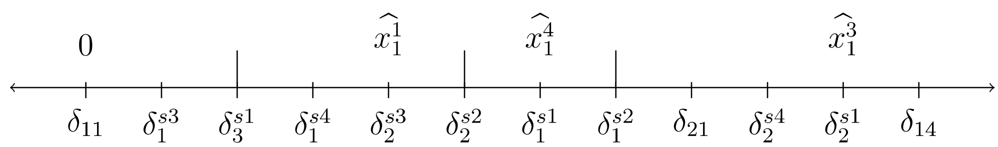
vii. For $p_1^4 \leq p_1 < p_1^{16}$:



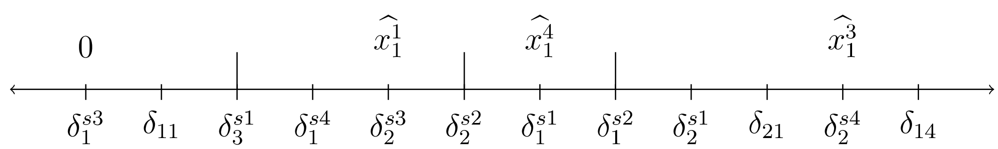
viii. For $p_1^{16} \leq p_1 < p_1^3$:



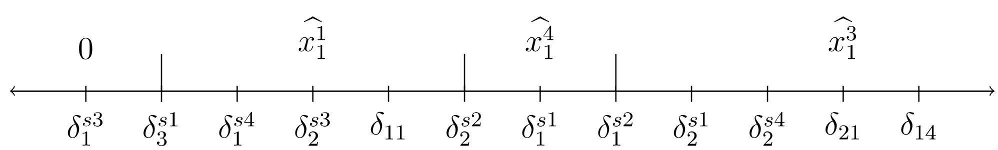
ix. For $p_1^3 \leq p_1 < p_1^{11}$:



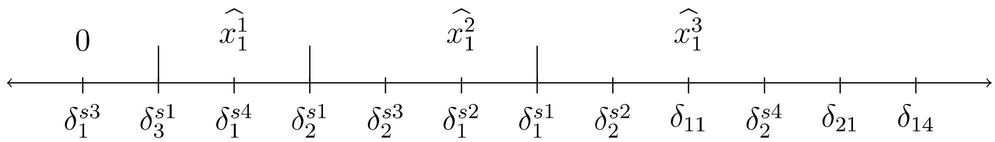
x. For $p_1^{11} \leq p_1 < p_1^5$:



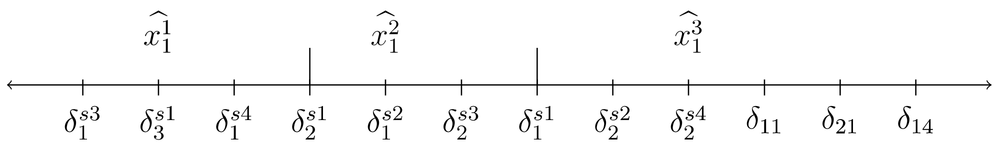
xi. For $p_1^5 \leq p_1 < p_1^1$:



xii. For $p_1^1 \leq p_1 < p_1^{13}$:

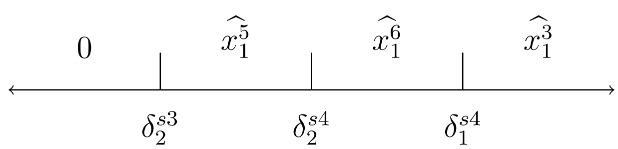


xiii. For $p_1^{13} \leq p_1 < p_1^{14}$:

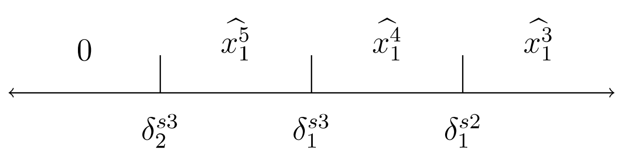


From above comparisons, we observe and define unique optimal solutions as follows:

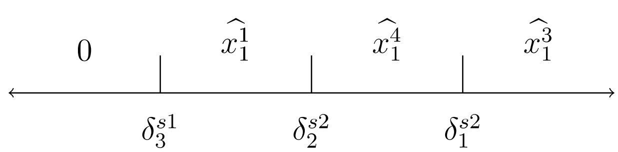
- For $p_1 < p_1^6$:



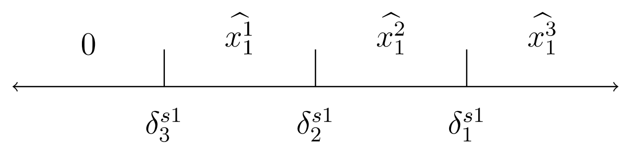
- For $p_1^6 \leq p_1 < p_1^4$:



- For $p_1^4 \leq p_1 < p_1^1$:



- For $p_1^1 \leq p_1$:



This proves Proposition 2.5. □

A.9 Proposition 6

Proof. Proof of Proposition 2.6. Using $x_s^*(x_m)$ from Proposition 2.1, and substituting in beekeeper's period 1 problem.

$$\pi_1\Bigg(x_m, x_s^*(x_m); x_1\Bigg) = p_1(x_1 - x_m) - c_m(x_m)^2 - c_o(x_1 - x_m)^2 - c_b x_1 \\ +\delta\left[\frac{\theta^2}{4c_o} + p_{b_1}(x_1 x_m) + \beta p_{b_1} x_m\right] \tag{A.13}$$

We write (A.13) as: $\pi_{1r}(x_m) = f(x_m) \ + \delta\beta p_{b_1} x_m$. Therefore P_{1r}^b in Section 2.8 can be written as:

$\underset{max_{x_m \geq 0}}{\mathbb{E}(u(x_m))} \ = \ \Bigg[\mathbb{E}\Bigg(- \exp(-r((f(x_m) + \delta\beta p_{b_1} x_m))\Bigg)\Bigg]$, where r is a risk aversion coefficient. Using $\mathbb{E}(\exp(tx) = \ tu + \frac{t^2\sigma^2}{2}$, when $x \sim \mathcal{N}(\mu, \sigma^2)$, also $\mathbb{E}(u(z)) \ = u(z_o)$, where z_o is certainty equivalent. Beekeeper's first period problem under risk averse producer is

$$\underset{max_{x_m \geq 0}}{\pi_{1r}^b(x_m)} = f(x_m) + \delta\beta p_{b_1} x_m - \frac{r\sigma_\beta^2 \delta^2 p_{b_1}^2 x_m^2}{2}$$

We observe that the risk averse beekeeper's objective function is concave in x_m, and the optimization problem $\max_{x_m \geq 0}$ is a convex program. The KKT first order condition (FOC) is necessary and sufficient to demonstrate optimality. The KKT FOC is described as $\partial\pi_{1r}^{b}(x_m)/\partial x_m = 0$, suggesting that $\widehat{x_m^r} = \dfrac{2c_o x_1 + \delta k_{\beta_o} p_{p_1} - p_1}{2(c_o + c_m) + r\sigma_{\beta_o}^2 \delta^2 p_{b_1}^2}$ satisfies the FOC condition. The constraint $x_m \geq 0$ implies that x_m^r as described in 2.6 is indeed optimal. □

A.10 Additional Notes

A.10.1 Proposition 2

The optimal capacity building and honey production strategy for the beekeeper can be summarized as follows:

i. For $\delta < \delta_{11}$:

   (a) For $x_1 < x_{14}$, it is optimal to neither migrate in the first period, nor sell bee boxes in the beginning of the second period.

   (b) For $x_{14} \leq x_1 < x_{13}$, it is optimal for the beekeeper to not to migrate in the first period but sell bee boxes partially, given by $x_s^*(x_m^* = 0)$, in the beginning of the second period.

   (c) For $x_{13} \leq x_1$, it is optimal for the beekeeper to migrate $\widehat{x_m}$ boxes in the first period and also sell bee boxes partially in the beginning of the second period, given by $x_s^*(x_m^* = \widehat{x_m})$.

ii. For $\delta_{11} \leq \delta < \delta_{21}$:

   (a) For $x_1 < x_{23}$, it is optimal to neither migrate in the first period nor sell boxes in the beginning of the second period.

   (b) For $x_{23} \leq x_1 < x_{11}$, it is optimal for the beekeeper to migrate $\widetilde{x_m}$ boxes in the first period, but not to sell boxes in the beginning of the second period.

(c) For $x_{11} \leq x_1$, it is optimal for the beekeeper to migrate $\widehat{x_m}$ boxes in the first period and sell bee boxes partially in the beginning of the second period, given by $x_s^*(x_m^* = \widehat{x_m})$.

iii. For $\delta_{21} \leq \delta < \delta_{14}$:

(a) For $x_1 < x_{22}$, it is optimal to migrate all the bee boxes that is x_1, in the first period, but not to sell boxes in the beginning of the second period.

(b) For $x_{22} \leq x_1 < x_{11}$, it is optimal for the beekeeper to migrate $\widetilde{x_m}$ boxes in the first period, but not to sell boxes in the beginning of the second period.

(c) For $x_{11} \leq x_1$, it is optimal for the beekeeper to migrate $\widehat{x_m}$ in the first period and sell $x_s^*(x_m^* = \widehat{x_m})$ boxes in the beginning of the second period.

iv. For $\delta_{14} \leq \delta < min\left(1, \frac{1}{k_\beta}\right)$:

(a) For $x_1 < x_{15}$, it is optimal to migrate all the bee boxes, that is x_1, in the first period, but not to sell boxes in the beginning of the second period.

(b) For $x_{15} \leq x_1 < x_{12}$, it is optimal for the beekeeper to migrate all the boxes that is x_1, in the first period and sell $x_s^*(x_m^* = x_1)$ boxes in the beginning of the second period.

(c) For $x_{12} \leq x_1$, it is optimal for the beekeeper to migrate $\widehat{x_m}$ in the first period and sell $x_s^*(x_m^* = \widehat{x_m})$ boxes in the beginning of the second period.

A.10.2 Proposition 4

i. For $\delta < \delta_{11}^u$:

(a) For $x_1 < x^u_{14}$, it is optimal to neither migrate in the first period, nor sell bee boxes in the beginning of the second period.

(b) For $x^u_{14} \leq x_1 < x^u_{13}$, it is optimal for the beekeeper to not to migrate in the first period but sell bee boxes partially, given by $x^*_s(x^*_m = 0, \beta_{l,h})$, in the beginning of the second period.

(c) For $x^u_{13} \leq x_1$, it is optimal for the beekeeper to migrate $\widehat{x_m}^u$ boxes in the first period and also sell bee boxes partially in the beginning of the second period, given by $x^*_s(x^*_m = \widehat{x_m}, \beta_{l,h})$.

ii. For $\delta^u_{11} \leq \delta < \delta^u_{31}$:

(a) For $x_1 < x^u_{33}$, it is optimal to neither migrate in the first period nor sell boxes in the beginning of the second period.

(b) For $x^u_{33} \leq x_1 < x^u_{31}$, it is optimal for the beekeeper to migrate $\widehat{\widehat{x^u_m}}$ boxes in the first period, but not to sell boxes in the beginning of the second period.

(c) For $x^u_{31} \leq x_1 < x^u_{11}$, it is optimal for the beekeeper to migrate $\widetilde{x_m}^u$ boxes in the first period and sell bee boxes partially in the beginning of the second period, given by $x^*_s(x^*_m = \widetilde{x_m}^u, \beta_{l,h})$.

(d) For $x^u_{11} \leq x_1$, it is optimal for the beekeeper to migrate $\widehat{x_m}^u$ in the first period and sell $x^*_s(x^*_m = \widehat{x_m}^u, \beta_{l,h})$ boxes in the beginning of the second period.

iii. For $\delta^u_{31} \leq \delta < \delta^u_{23}$:

(a) For $x_1 < x^u_{32}$, it is optimal to migrate all the bee boxes that is x_1, in the first period, but not to sell boxes in the beginning of the second period.

(b) For $x_{32}^u \leq x_1 < x_{31}^u$, it is optimal for the beekeeper to migrate $\widehat{\widehat{x_m^u}}$ boxes in the first period, but not to sell boxes in the beginning of the second period.

(c) For $x_{31}^u \leq x_1 < x_{11}^u$, it is optimal for the beekeeper to migrate $\widetilde{x_m}^u$ boxes in the first period and sell bee boxes partially in the beginning of the second period, given by $x_s^*(x_m^* = \widetilde{x_m}^u, \beta_{l,h})$.

(d) For $x_{11}^u \leq x_1$, it is optimal for the beekeeper to migrate $\widehat{x_m}^u$ in the first period and sell $x_s^*(x_m^* = \widehat{x_m}^u, \beta_{l,h})$ boxes in the beginning of the second period.

iv. For $\delta_{23}^u \leq \delta < \delta_{14}^u$:

(a) For $x_1 < x_{25}^u$, it is optimal to migrate all the bee boxes, that is x_1, in the first period, but not to sell boxes in the beginning of the second period.

(b) For $x_{25}^u \leq x_1 < x_{23}^u$, it is optimal for the beekeeper to migrate all the boxes that is x_1, in the first period and sell $x_s^*(x_m^* = x_1, \beta_{l,h})$ boxes in the beginning of the second period.

(c) For $x_{23}^u \leq x_1 < x_{11}^u$, it is optimal for the beekeeper to migrate $\widetilde{x_m}^u$ boxes in the first period and sell bee boxes partially in the beginning of the second period, given by $x_s^*(x_m^* = \widetilde{x_m}^u, \beta_{l,h})$.

(d) For $x_{11}^u \leq x_1$, it is optimal for the beekeeper to migrate $\widehat{x_m}^u$ in the first period and sell $x_s^*(x_m^* = \widehat{x_m}^u, \beta_{l,h})$ boxes in the beginning of the second period.

v. For $\delta_{14}^u \leq \delta < min\left(1, \frac{1}{\mathbb{E}(k_\beta)}\right)$:

(a) For $x_1 < x_{25}^u$, it is optimal to migrate all the bee boxes, that is x_1, in the first period, but not to sell boxes in the beginning of the second period.

(b) For $x_{25}^u \leq x_1 < x_{15}^u$, it is optimal for the beekeeper to migrate all the boxes that is x_1, in the first period and sell $x_s^*(x_m^* = x_1, \beta_{l,h})$ boxes in the beginning of the second period.

(c) For $x_{15}^u \leq x_1 < x_{12}^u$, it is optimal for the beekeeper to migrate $\widetilde{x_m}^u$ boxes in the first period and sell bee boxes partially in the beginning of the second period, given by $x_s^*(x_m^* = \widetilde{x_m}^u, \beta_{l,h})$.

(d) For $x_{12}^u \leq x_1$, it is optimal for the beekeeper to migrate $\widehat{x_m}^u$ in the first period and sell $x_s^*(x_m^* = \widehat{x_m}, \beta_{l,h})$ boxes in the beginning of the second period.

Appendix B

Proofs of Study 2

Proof. Proof of Proposition 3.1. Consider the objective function $\pi_c(q_h, q_l, \beta)$ from (3.11) for given $\beta \in (0,1)$. We obtain

$$\partial\pi_c(q_h, q_l, \beta)/\partial q_h = -\beta k\{2\alpha q_h - \delta v_h \cdot [1 + ln(1+k)][1 + \theta(1-\beta) q_l]\}$$

$$\partial\pi_c(q_h, q_l, \beta)/\partial q_l = -(1-\beta) k\{2\alpha q_l - [\beta\theta\delta v_h [1 + ln(1+k)] \cdot q_h + v_l]\}$$

$$\partial\pi_c^2(q_h, q_l, \beta)/\partial q_h^2 = -2\alpha\beta k; \quad \text{and} \quad \partial\pi_c^2(q_h, q_l, \beta)/\partial q_l^2 = -2\alpha(1-\beta) k$$

$$\partial\pi_c^2(q_h, q_l, \beta)/\partial q_h q_l = \theta\delta v_h \beta(1-\beta) k \cdot [1 + ln(1+k)]$$

The determinant of the Hessian matrix for $\pi_c(q_h, q_l, \beta)$ is equal to $\beta(1-\beta) k^2 H_\beta^{S0}(\beta)$, where $H_\beta^{S0}(\beta)$ is as defined in (3.14). It may be observed that $H_\beta^{S0}(\beta)$ attains minimum at $\beta = 1/2$. Clearly, by the assumption $\alpha > \underline{\alpha} = \theta\delta v_h \cdot [1 + ln(1+k)]/4$, $H_\beta^{S0}(\beta) > 0$ for $\beta \in [0,1]$, and the determinant is positive definite. The first order conditions are necessary and sufficient to obtain optimal q_h

and q_l, i.e.,

$$q_h^{S0*}(q_l) = \delta v_h \cdot [1 + ln(1+k)][1 + \theta(1-\beta) q_l]/2\alpha \tag{B.1}$$

$$q_l^{S0*}(q_h) = [1 + ln(1+k)][\beta\theta\delta v_h \cdot q_h + v_l]/2\alpha \tag{B.2}$$

Now, solving $q_h^{S0*}(q_l)$ and $q_l^{S0*}(q_h)$ simultaneously, we obtain q_h^{S0*} and q_l^{S0*} as described in (3.12) and (3.13). It is direct to note that $q_h^{S0*}, q_l^{S0*} \geq 0$. □

Proof. Proof of Lemma 3.1. By substituting $q_h^{S0*}(\beta)$ and $q_l^{S0*}(\beta)$ as described in Proposition 3.1 into $\pi_c(q_h, q_l, \beta)$ defined in (3.11), we obtain the firm's objective function in β that is denoted by $\pi_c\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)$. For notational simplicity, we also define the firm's revenue function as $R\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right) = \left(\delta v_h^n q_h^{S0*}(\beta) - \alpha q_h^{S0*}(\beta)^2\right)\beta k + \left(v_l^n q_l^{S0*}(\beta) - \alpha q_l^{S0*}(\beta)^2\right)(1-\beta)k$. We obtain

$$\begin{aligned}
\partial R\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)/\partial\beta &= \Big[\left(\delta v_h^n q_h^{S0*}(\beta) - \alpha q_h^{S0*}(\beta)^2\right)k \\
&\quad + \left(\delta v_h^n \partial q_h^{S0*}(\beta)/\partial\beta - 2\alpha q_h^{S0*}(\beta)\,\partial q_h^{S0*}(\beta)/\partial\beta\right)\beta k\Big] \\
&\quad + \Big[-\left(v_l^n q_l^{S0*}(\beta) - \alpha q_l^{S0*}(\beta)^2\right)k + \left(v_l^n \partial q_l^{S0*}(\beta)/\partial\beta - 2\alpha q_l^{S0*}(\beta)\,\partial q_l^{S0*}(\beta)/\partial\beta\right)(1-\beta)k\Big] \\
\partial^2 R\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)/\partial\beta^2 &= \Bigg[2\left(\delta v_h^n \partial q_h^{S0*}(\beta)/\partial\beta - 2\alpha q_h^{S0*}(\beta)\,\partial q_h^{S0*}(\beta)/\partial\beta\right)k \\
&\quad + \left(\delta v_h^n \partial^2 q_h^{S0*}(\beta)/\partial\beta^2 - 2\alpha\left(\partial q_h^{S0*}(\beta)/\partial\beta\right)^2 - 2\alpha q_h^{S0*}(\beta)\,\partial^2 q_h^{S0*}(\beta)/\partial\beta^2\right)\beta k\Bigg] \\
&\quad + \Bigg[-2\left(v_l^n \partial q_l^{S0*}(\beta)/\partial\beta - 2\alpha q_l^{S0*}(\beta)\,\partial q_l^{S0*}(\beta)/\partial\beta\right)k \\
&\quad + \left(v_l^n \partial^2 q_l^{S0*}(\beta)/\partial\beta^2 - 2\alpha\left(\partial q_l^{S0*}(\beta)/\partial\beta\right)^2 - 2\alpha q_l^{S0*}(\beta)\,\partial^2 q_l^{S0*}(\beta)/\partial\beta^2\right)(1-\beta)k\Bigg]
\end{aligned}$$

where, $\partial q_h^{S0*}(\beta)/\partial\beta$ and $\partial q_l^{S0*}(\beta)/\partial\beta$ are as described in (B.8) and (B.9), respectively. Similarly, we obtain

$$\partial^2 q_h^{S0*}(\beta)/\partial\beta^2 = -\theta^2\delta^3 v_h^3 \cdot [1 + ln(1+k)]^3 \Big\{ -\theta^3\delta^2 v_h^2 v_l (1-\beta)^3 \cdot [1+\zeta ln(1+k)]^3 - 2\alpha\big\{\theta^2\delta^2 v_h^2 [1-3\beta(1-\beta)] \cdot [1+ln(1+k)]^2 - 2\alpha\big\{\theta v_l (2-3\beta) \cdot [1+ln(1+k)] + 2\alpha\big\}\big\}\Big\} / \left(H_\beta^{S0}(\beta)\right)^3 \quad \text{(B.3)}$$

$$\partial^2 q_l^{S0*}(\beta)/\partial\beta^2 = 2\theta^2\delta^2 v_h^2 \cdot [1 + ln(1+k)]^3 \Big\{\theta^3\delta^4 v_h^4 \beta^3 \cdot [1+ln(1+k)]^3 + 2\alpha\big\{\theta^2\delta^2 v_h^2 v_l [1-3\beta(1-\beta)] \cdot [1+ln(1+k)]^2 + 2\alpha\big\{\theta\delta^2 v_h^2 (1-3\beta) \cdot [1+ln(1+k)] - 2\alpha v_l\big\}\big\}\Big\} / \left(H_\beta^{S0}(\beta)\right)^3 \quad \text{(B.4)}$$

It may be noted that

$$\partial\frac{\pi_c\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)}{\partial\beta} = \frac{\partial R\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)}{\partial\beta} - 2c\beta k^2 \quad \text{(B.5)}$$

$$\frac{\partial^2\pi_c\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)}{\partial\beta^2} = \frac{\partial^2 R\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)}{\partial\beta^2} - 2ck^2 \quad \text{(B.6)}$$

Since $q_j^*(\beta)$, $j = l, h$, is independent of c, $\partial^2 R\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)/\partial\beta^2$ is also independent of c. By defining $\underline{c} = \max\left\{\partial^2 R\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)/\partial\beta^2/2k^2 | \beta \in [0,1]\right\}$, we note that $\partial^2\pi_c\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)/\partial\beta^2 < 0$ for $c > \underline{c}$. Likewise, the firm's objective function is strictly concave in β.

$$\partial v_h^n(\beta_t)/\partial\beta = v_h \cdot [1+ln(1+k)] \cdot \theta\left[(1-\beta_t)\,\partial q_l^{S0*}(\beta_t)/\partial\beta - q_l^{S0*}(\beta_t)\right] \tag{B.7}$$

$$\partial q_h^{S0*}(\beta_t)/\partial\beta = \theta\delta v_h \cdot [1+ln(1+k)]^2 \Big\{\theta^2\delta^2 v_h^2 v_l (1-\beta_t)^2 \cdot [1+ln(1+k)]^2 + 2\alpha\left\{\theta\delta^2 v_h^2(1-2\beta_t)\cdot[1+ln(1+k)] - 2\alpha v_l\right\}\Big\}/\left(H_\beta^{S0}(\beta_t)\right)^2 \tag{B.8}$$

$$\partial q_l^{S0*}(\beta_t)/\partial\beta = \theta\delta^2 v_h^2 \cdot [1+ln(1+k)]^2 \Big\{\theta^2\delta^2 v_h^2\beta_t^2 \cdot [1+\zeta ln(1+k)]^2 - 2\alpha\left\{\theta v_l(1-2\beta_t)\cdot[1+ln(1+k)] + 2\alpha\right\}\Big\}/\left(H_\beta^{S0}(\beta_t)\right)^2 \tag{B.9}$$

□

Proof. Proof of Proposition 3.3. From Lemma 3.1, the optimal β that maximizes $\pi_c\left(q_h^{S0*}(\beta), q_l^{S0*}(\beta), \beta\right)$, denoted by β_t, can be obtained using the first order condition, i.e., $\partial\pi_c\left(q_h^{S0*}(\beta_t), q_l^{S0*}(\beta_t), \beta_t\right)/\partial\beta = 0$ obtained using (B.5) that is described in (3.17). By the strict concavity of the objective function, the solution is unique. Clearly, the solution β_t is optimal for the unconstrained problem obtained by ignoring the feasibility condition $\beta \in (0,1)$. The feasibility of the solution obtained from the first order condition is ensured by defining the optimal solution as $\beta^{S0*} = \max\{\epsilon, \min\{\beta_t, 1-\epsilon\}\}$, $\lim \epsilon = 0$, for the firm's problem as defined in (3.11). □

Proof. Proof of Proposition 3.4. By the strict concavity of the objective function as described in Lemma 3.1, it may be noted that $\beta^{S0*} = \epsilon$, $\lim \epsilon = 0$, when $\partial\pi_c\left(q_h^{S0*}(\beta_t), q_l^{S0*}(\beta_t), \beta_t\right)/\partial\beta \leq 0$ for $\beta_t = 0$. Thereby, by substituting $\beta_t = 0$ (in the limit) into the condition $\partial\pi_c\left(q_h^{S0*}(\beta_t), q_l^{S0*}(\beta_t), \beta_t\right)/\partial\beta \leq 0$ using (B.5), we obtain

$$\left\{\frac{[1+ln\,(1+k)]^2\,k}{16\alpha^3}\right\}\Bigg\{\{2\alpha v_l+\delta v_h\cdot[2\alpha+\theta v_l\cdot[1+ln\,(1+k)]]\}\cdot$$
$$\{-2\alpha v_l+\delta v_h\cdot[2\alpha+\theta v_l\cdot[1+ln\,(1+k)]]\}\Bigg\}\le 0 \tag{B.10}$$

Clearly, the condition is satisfied for $\delta\le\underline{\delta}^{S0}$, where $\underline{\delta}^{S0}$ is as described in (3.18). It is immediate to note that $\underline{\delta}^{S0}\ge 0$. □

Proof. Proof of Proposition 3.5. The proof parallels that for Proposition 3.4. By the strict concavity of the objective function as described in Lemma 3.1, it may be noted that $\beta^{S0*}=1-\epsilon,\ \lim\epsilon=0$, when $\partial\pi_c\left(q_h^{S0*}(\beta_t),q_l^{S0*}(\beta_t),\beta_t\right)/\partial\beta\ge 0$ for $\beta_t=1$. By substituting $\beta_t=1$ into the condition $\partial\pi_c\left(q_h^{S0*}(\beta_t),q_l^{S0*}(\beta_t),\beta_t\right)/\partial\beta\ge 0$ using (B.5), we obtain

$$\left\{\frac{[1+ln\,(1+k)]^2\,k}{16\alpha^3}\right\}\Bigg\{-4\alpha^2v_l^2+\delta^2v_h^2\{4\alpha\cdot\{\alpha-\theta v_l\cdot$$
$$[1+ln\,(1+k)]\}-\theta^2\delta^2v_h^2\cdot[1+ln\,(1+k)]^2\}\Bigg\}-ck^2\ge 0 \tag{B.11}$$

Now, let us define $\overline{\delta}_i^{S0}$ as the non-negative root of the L.H.S. of (B.11). We obtain $\overline{\delta}_i^{S0}=\sqrt{2\alpha\Delta_\alpha}/\theta v_h\cdot[1+ln\,(1+k)]$.

When $\alpha\ge\overline{\alpha}$, it may be noted that $\alpha\ge\theta v_l\cdot[1+ln\,(1+k)]$. Now, we can show that $\Delta_\alpha\ge 0$ as $\{\alpha-\theta v_l\cdot[1+ln\,(1+k)]\}^2-\alpha(\alpha-\overline{\alpha})=\theta^2\Big\{v_l^2\cdot[1+ln\,(1+k)]^2+8\alpha ck\,[1+(1-\rho)\,k]\,/\,(1+k)\Big\}\ge 0$. Clearly, when $\alpha<\overline{\alpha}$, $\partial\pi\left(q_h^{S0*}(\beta_t),q_l^{S0*}(\beta_t),\beta_t\right)/\partial\beta<0$ for $\beta_t=1$.

Considering $\delta\in[0,1]$, we can define $\overline{\delta}^{S0}$ as described in (3.21); the rest of the proof is straightforward. □

Proof. Proof of Corollary 3.1. From (3.18), we obtain

$$1-\underline{\delta}^{S0}=\frac{2\alpha\left(v_h-v_l\right)+\theta v_h v_l\cdot\left[1+ln\left(1+k\right)\right]}{v_h\left\{2\alpha+\theta v_l\cdot\left[1+ln\left(1+k\right)\right]\right\}}$$

By the assumption $v_h \geq v_l \cdot$, we obtain $1-\underline{\delta}^{S0}\geq 0$. Clearly, $\underline{\delta}^{S0}>0$.

Consider $\alpha>\overline{\alpha}$. In this case, it is sufficient to show that $\overline{\delta}^{S0}\geq\underline{\delta}^{S0}$. Furthermore, recall that $\underline{\delta}^{S0},\overline{\delta}^{S0}$ are both increasing in α. Also, $\underline{\delta}^{S0},\overline{\delta}^{S0}\geq 0$. Define $\Delta_{\delta}^2=\left(\overline{\delta}^{S0}\right)^2-\left(\underline{\delta}^{S0}\right)^2$, we obtain

$$\Delta_{\delta}^2=\frac{2\alpha\left\{\alpha\left\{3\alpha^2-5\theta^2v_l^2\cdot\left[1+ln\left(1+k\right)\right]^2\right\}+\left\{\alpha^3-\theta^3v_l^3\cdot\left[1+ln\left(1+k\right)\right]^3\right\}\right\}}{\theta^2v_h^2\cdot\left[1+ln\left(1+k\right)\right]^2\left\{2\alpha+\theta v_l\cdot\left[1+ln\left(1+k\right)\right]\right\}^2}$$

$$\begin{aligned}\frac{\partial\Delta_{\delta}^2}{\partial\alpha}=&\frac{\left\{16\alpha^4-\theta^4v_l^4\cdot\left[1+ln\left(1+k\right)\right]^4\right\}}{\theta^2v_h^2\cdot\left[1+ln\left(1+k\right)\right]^2\left\{2\alpha+\theta v_l\cdot\left[1+ln\left(1+k\right)\right]\right\}^3}\\&+\frac{8\alpha\theta v_l\cdot\left[1+ln\left(1+k\right)\right]\left\{2\alpha^2-\theta^2v_l^2\cdot\left[1+ln\left(1+k\right)\right]^2\right\}}{\theta^2v_h^2\cdot\left[1+ln\left(1+k\right)\right]^2\cdot\left\{2\alpha+\theta v_l\cdot\left[1+ln\left(1+k\right)\right]\right\}^3}\end{aligned}$$

From (3.19), it may be noted that that $\overline{\alpha}>\theta v_l\cdot exp\{-q_c\}\cdot\left[1+\zeta ln\left(1+k\right)\right]\geq 0$. Note that $\partial\Delta_{\delta}^2/\partial\alpha\geq 0$ implies that Δ_{δ}^2 is increasing in α. Thereby, to show that $\overline{\delta}^{S0}\geq\underline{\delta}^{S0}$ for $\alpha\geq\overline{\alpha}$, it is sufficient to show that $\overline{\delta}^{S0}\geq\underline{\delta}^{S0}$ for $\alpha=\overline{\alpha}$. It is direct to note from Δ_{δ}^2 as described above that $\Delta_{\delta}^2\left(\overline{\alpha}\right)\geq 0$. Hence, for $\alpha\geq\overline{\alpha}$, we obtain $\overline{\delta}^{S0}\geq\underline{\delta}^{S0}$.

From the above and using Propositions 3.4 and 3.5, the remainder of the proof directly follows. □

Proof. Proof of Lemma 3.2. Given $\beta\in(0,1)$ and the firm's optimal product quality levels as described in Proposition 3.6, the monotonicity property for the optimal solution under asymmetric information is given as follows:

$$\beta v_h \cdot \left\{2\alpha - \delta^2 \left\{2\alpha + \theta v_l \cdot [1 + ln\,(1+k)]\right\}\right\}$$
$$- \left\{2\alpha v_l - \delta^2 v_h \cdot \left\{2\alpha + \theta v_l \cdot [1 + ln\,(1+k)]\right\}\right\} \geq 0 \qquad \text{(B.12)}$$

Define $\underline{\delta}_{c1} = \sqrt{2\alpha / \left\{2\alpha + \theta v_l \cdot [1 + ln\,(1+k)]\right\}}$. For $\delta < (\geq)\, \underline{\delta}_{c1}$, the coefficient of β, $v_h \cdot \left\{2\alpha - \delta^2 \left\{2\alpha + \theta v_l \cdot [1 + ln\,(1+k)]\right\}\right\} < (\geq)\, 0$. Similarly, for $\delta < (\geq)\, \underline{\delta}_c$, we note that $\left\{2\alpha v_l - \delta^2 v_h \cdot \left\{2\alpha + \theta v_l \cdot [1 + ln\,(1+k)]\right\}\right\} < (\geq)\, 0$. By the assumption $v_h \geq v_l$, we obtain $\underline{\delta}_c < \underline{\delta}_{c1}$.

Consider $\delta \leq \underline{\delta}_c$. Clearly, the monotonicity condition (B.12) does not satisfy for $\beta \in (0,1)$.

Consider $\delta\, [\underline{\delta}_c, \underline{\delta}_{c1})$. The LHS of (B.12) is decreasing in β. Clearly, the monotonicity condition satisfies for $\beta = 0$. Also, for $\beta = 1$, the LHS of (B.12) is equal to $2\alpha\,(v_h - v_l) \geq 0$. It is immediate that the condition satisfies for $\beta \in (0,1)$.

Consider $\delta \geq \underline{\delta}_{c1}$. The LHS of (B.12) is increasing in β and the monotonicity condition satisfies for $\beta \in (0,1)$.

The rest of the proof is straightforward. □

Proof. Proof of Proposition 3.7.

$$\partial v_h^n(\beta_t)/\partial\beta = \theta v_h \cdot [1 + ln(1+k)] \cdot \left[(1-\beta_t)\,\partial q_l^{S1*}(\beta_t,\phi)/\partial\beta - q_l^{S1*}(\beta_t,\phi)\right] \quad \text{(B.13)}$$

$$\partial p_l^{S1*}(\beta_t,\phi)/\partial\beta = v_l \cdot [1 + ln(1+k)]\,\partial q_l^{S1*}(\beta_t,\phi)/\partial\beta \quad \text{(B.14)}$$

$$\begin{aligned}\partial p_h^{S1*}(\beta,\phi) &= \delta v_h \cdot [1 + ln(1+k)] \cdot \left\{\left[1 + \theta(1-\beta_t)\,q_l^{S1*}(\beta_t,\phi)\right]\partial q_h^{S1*}(\beta_t,\phi)/\partial\beta\right.\\ &\left.+\theta(1-\beta_t)\,q_h^{S1*}(\beta_t,\phi)\,\partial q_l^{S1*}(\beta_t,\phi)/\partial\beta - \theta q_l^{S1*}(\beta_t,\phi)\,q_h^{S1*}(\beta_t,\phi)\right\}\\ &-\left\{v_h \cdot \left[1 + \theta(1-\beta_t)\,q_l^{S1*}(\beta_t,\phi)\right] - v_l\right\}[1 + ln(1+k)]\,\partial q_l^{S1*}(\beta_t,\phi)/\partial\beta\\ &-\left\{v_h \cdot \left[\theta(1-\beta_t)\,\partial q_l^{S1*}(\beta_t,\phi)/\partial\beta - \theta q_l^{S1*}(\beta_t,\phi)\right]\right\}[1 + ln(1+k)]\,q_l^{S1*}(\beta_t,\phi)\end{aligned} \quad \text{(B.15)}$$

$$\begin{aligned}\partial q_h^{S1*}(\beta_t)/\partial\beta &= \theta\delta v_h \cdot [1 + ln(1+k)]^2 \left\{\theta^2\delta^2 v_h^2 \cdot [1 + ln(1+k)]^2\right.\\ &\left[v_h \cdot \beta_t^2(\phi-1) + v_l \cdot \left(1 + \phi\beta_t^2 - 2\beta_t\right)\right] + 2\alpha\,\{2\alpha\,[v_h \cdot (1-\phi)\\ &\left.+\phi v_l] + \theta\delta^2 v_h^2(1-2\beta_t) \cdot [1 + ln(1+k)]\}\right\}/\left(H_\beta^{S1}(\beta,\phi)\right)^2\end{aligned} \quad \text{(B.16)}$$

$$\begin{aligned}\partial q_l^{S1*}(\beta_t,\phi)/\partial\beta &= \theta\delta v_h \cdot [1 + ln(1+k)]^2 \left\{\theta^2\delta^2 v_h^2\beta_t^2 \cdot\right.\\ &\left.[1 + ln(1+k)]^2 - 2\alpha\,\{\theta v_l(1-2\beta_t) \cdot [1 + ln(1+k)] + 2\alpha\}\right\}/\left(H_\beta^{S1}(\beta,\phi)\right)^2\end{aligned} \quad \text{(B.17)}$$

□

Proof. Proof of Proposition 3.8. From Lemma 3.2, the proof parallels that for Proposition 3.4, and hence, omitted. □

Appendix C

Proofs of Study 3

Proof. Proof of Proposition 4.1

From (4.4), it is noted that the firm's objective function is jointly concave in x_i and q_i, and the optimization problem $\max_{x_i, q_i}$ is a convex program. The KKT first order condition (FOC) is necessary and sufficient to demonstrate optimality of a solution. The condition for the hessian matrix to be negative semi-definite give $(4c - \mu^2) > 0$. The KKT FOC is described as $\partial\pi_{f_i}/\partial x_i, \partial\pi_{f_i}/\partial q_i = 0$, suggesting that $x_i = \dfrac{\mu\gamma\bar{s}}{(4c - \mu^2)s_i}$ and $q_i = \dfrac{(2c + \mu)\gamma\bar{s} - (4c - \mu^2)s_i}{(4c - \mu^2)}$ satisfies the FOC condition. The constraint $q_i \geq 0,\ s_i x_i \geq \bar{s},\ q_i \leq y_i$ implies that $\widehat{x_i}$ *and* $\widehat{q_i}$ as described within the bounds in (4.6) is indeed optimal. □

Proof. Proof of Corollary 4.1

Results obtained in Corollary 4.1 is from the direct comparisons of the results obtained in Proposition 4.1 with the constrains as described in (4.4).

Also, it is noted that $\partial\widehat{x_i}/\partial\mu = \dfrac{(1 + 4\mu^2)\gamma\bar{s}}{(4c - \mu^2)s_i} \geq 0.$ □

Proof. Proof of Theorem 4.1

We define consumer surplus as $\int_0^{\widehat{q_i}} p_i\left(\bar{s}, x_i, q_i\right) dq_i - p_i(\bar{s}, \widehat{x_i}, \widehat{q_i}) * \widehat{q_i}$, which gives the consumer surplus as defined in (4.9). Also, firm's profit, π_{f_i} at $\widehat{x_i}$ *and* $\widehat{q_i}$, gives the profit as defined in (4.10). □

Proof. Proof of Proposition 4.2

From (4.5), it is noted that the government's objective function is convex in $\bar{s}$ and the optimization problem $\min_{\bar{s}}$ is a convex program. The KKT first order condition (FOC) is necessary and sufficient to demonstrate optimality of a solution. The KKT FOC is described as $\partial C_{sa}/\partial \bar{s} = 0$,suggesting that $\widehat{\bar{s}} = \dfrac{k_4(\theta s_h y_h + (1-\theta)s_l y_l)}{\mu\gamma(\theta y_h + (1-\theta)y_l)}$ satisfies the FOC condition. The constraint $\bar{s_{1_h}} \leq \bar{s} \leq \bar{s_{2_h}}$ implies that $\widehat{s}$ is indeed the optimal solution.

On comparing $\widehat{s}$ with the lower and upper bound, $\bar{s_{1_h}} \leq \bar{s} \leq \bar{s_{2_h}}$, we get upper and lower bounds on the government policy defined in μ, that is defined in the Proposition 4.2. □

Proof. Proof of Theorem 4.2

From (4.18), similar to the proof of Proposition 4.1, it is noted that the firm's objective function is jointly concave in x_i and q_i, and the optimization problem $\max_{x_i,q_i}$ is a convex program. The KKT first order condition (FOC) is necessary and sufficient to demonstrate optimality of a solution. The condition for the hessian matrix to be negative semi-definite give $(4c(1-\beta) - (\mu+\beta)^2) \ > 0$. The KKT FOC is described as $\partial\pi_{f_i^c}/\partial x_i, \partial\pi_{f_i^c}/\partial q_i = 0$, suggesting that $\widehat{q_i^c}$ and $\widehat{x_i^c}$ satisfies the FOC condition. The constraint $q_i \geq 0,\ s_i x_i \geq \bar{s},\ q_i \leq y_i$ implies that $\widehat{x_i^c}$ *and* $\widehat{q_i^c}$ as described within the bounds in (4.20) is indeed optimal. □

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