Online Appendices to "Value and Design of Traceability-Driven Blockchains"

A. Comparison of Papers on Supply Chain Quality Management

Table A.1 Comparison of Papers on Supply Chain Quality Management

Paper	Contract/mechanism	Supply chain structure	Quality decision
Baiman et al. (2000)	Product appraisal	1 supplier + 1 buyer	Continuous
Balachandran and Radhakrishnan (2005)	Penalty based on incoming inspection; Penalty based on external failure cause	1 supplier + 1 buyer	Continuous
Hwang et al. (2006)	Vendor certification; Product appraisal	1 supplier + 1 buyer	Binary
Chao et al. (2009)	Cost sharing based on selective root cause analysis; Partial cost sharing based on complete root cause analysis	1 supplier + 1 buyer	Continuous
Babich and Tang (2012)	Deferred payment; Inspection; Combined mechanism	1 supplier + 1 buyer	Binary
Rui and Lai (2015)	Deferred payment; Inspection	1 supplier + 1 buyer	Binary
Lee and Li (2018)	Incoming product inspection	1 supplier + 1 buyer	Continuous
Nikoofal and Gümüş (2018)	Quality-at-the-end contract (inspect end product's quality); Quality-at-the-source contract (audit supplier's quality effort)	1 supplier + 1 buyer	Binary
Bondareva and Pinker (2019)	Inspection (and relational contract)	1 supplier + 1 buyer	Continuous
Baiman et al. (2004)	Acceptable quality level contract; Quality-based incentive pricing contract; Group warranty contract	N suppliers + 1 buyer (assembly supply chain)	Continuous
Dong et al. (2016)	Inspection-based mechanism; External failure-based mechanism	1 supplier + 1 buyer & 1 supplier + 1 outsourced manufacturer + 1 buyer (serial supply chain)	Binary
Mu et al. (2016)	Individual testing; Mixed testing	N suppliers + 1 or 2 buyers	Binary
This paper	Contract with traceability; Contract without traceability	2 suppliers + 1 buyer (serial & parallel supply chains)	Continuous

B. Table of Notation

Table B.1 Table of Notation

Parameters	
p	Retail price
l	Net loss incurred by the buyer under defect, with $l > -p$
θ	Multiplier in the suppliers' quality cost function
γ	Efficiency measure of the suppliers' quality improvement, with $\gamma > 1$
N/T	Superscript for the case without/with traceability
$\ddagger/\dagger$	Superscript for the equilibrium in a serial/parallel supply chain
Decision variables	
q_i	Quality level chosen by supplier i, with $q_i \in [0,1]$, $i \in \{1,2\}$
w_i	Wholesale price paid to supplier i, $i \in \{1,2\}$

C. Data Permission and Consensus Mechanism

C.1. Model

C.1.1. A Serial Supply Chain. Under restricted data permission, the buyer's contracting problem in a serial supply chain is formulated as

$$\begin{aligned}
&\max_{w_1,w_2} \quad \pi_B(w_1,w_2|\tilde{q}_1(w_1),\tilde{q}_2(w_2)) = p\prod_{i=1}^{2}\tilde{q}_i(w_i) - l\left[1-\prod_{i=1}^{2}\tilde{q}_i(w_i)\right] - \sum_{i=1}^{2} w_i\tilde{q}_i(w_i) \\
&\text{s.t.} \quad \begin{cases} \pi_{S_i}(\tilde{q}_i(w_i)|w_i) \geqslant 0, i\in\{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(w_i) = \arg\max_{q_i} \ \pi_{S_i}(q_i|w_i), i\in\{1,2\} & (\text{IC}_i) \end{cases}
\end{aligned} \tag{C.1}$$

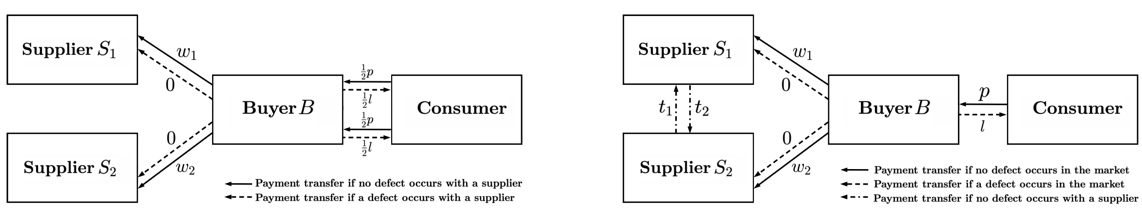
where $\pi_{S_i}(q_i|w_i) = w_iq_i - C(q_i)$ for $i\in\{1,2\}$.

C.1.2. A Parallel Supply Chain. Under restricted data permission, the buyer's contracting problem in a parallel supply chain is formulated as

$$\begin{aligned}
&\max_{\mathbf{w}} \quad \pi_B(\mathbf{w}|\tilde{\mathbf{q}}(\mathbf{w})) = p\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) - l\left[1-\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w})\right] - \left(\sum_{i=1}^{2} w_i\right)\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) \\
&\text{s.t.} \quad \begin{cases} \pi_{S_i}(\tilde{q}_i(\mathbf{w}),\tilde{t}_{-i}(\mathbf{w})|w_i,\tilde{t}_i(\mathbf{w}),\tilde{q}_{-i}(\mathbf{w})) \geqslant 0, i\in\{1,2\} & (\text{IR}_i) \\ \left\{\tilde{q}_i(\mathbf{w}),\tilde{t}_{-i}(\mathbf{w})\right\} = \arg\max_{q_i,t_{-i}} \ \pi_{S_i}(q_i,t_{-i}|w_i,t_i,q_{-i}), i\in\{1,2\} & (\text{IC}_i) \end{cases}
\end{aligned} \tag{C.2}$$

where $\pi_{S_i}(q_i,t_{-i}|w_i,t_i,q_{-i}) = w_iq_iq_{-i} + t_iq_i(1-q_{-i}) - t_{-i}q_{-i}(1-q_i) - C(q_i)$ for $i\in\{1,2\}$.

Figure C.1 Illustration of Contracts under Different Data Permission Schemes in a Parallel Supply Chain



(a) Unrestricted Data Permission (b) Restricted Data Permission

C.2. Supplemental Results

Proposition C.1 (Equilibrium under Restricted Data Permission in a Parallel Supply Chain). *In a parallel supply chain under restricted data permission, there exists a unique equilibrium such that the buyer offers wholesale price* $w_i^{R\dagger} = \frac{p+l}{\gamma}$ *to supplier* $i\in\{1,2\}$*, and supplier* i *offers transfer payment* $t_i^{R\dagger}=0$ *to supplier* $-i$ *and chooses quality level* $q_i^{R\dagger} = \left(\frac{p+l}{\theta\gamma^2}\right)^{\frac{1}{\gamma-2}}$.

Theorem C.1 (Optimal Data Permission in a Parallel Supply Chain). *In a parallel supply chain, the total supply chain profit is always higher under unrestricted data permission.*

Proposition C.2 (Individual Firm Preferences for Data Permission in a Parallel Supply Chain). *In a parallel supply chain,*

(a) *the buyer always prefers unrestricted data permission;*

(b) *the suppliers prefer unrestricted data permission if $l \leqslant \bar{l}$, and prefer restricted data permission if $l > \bar{l}$.*

Theorem C.2 (Data Permission Chosen in a Parallel Supply Chain). *In a parallel supply chain,*

(a) *under the centralized consensus mechanism, unrestricted data permission will always be chosen, which is the optimal policy for the supply chain;*

(b) *under the decentralized consensus mechanism,*

(i) *if $l \leqslant \bar{l}$, unrestricted data permission will be chosen, which is the optimal policy for the supply chain;*

(ii) *if $l > \bar{l}$, restricted data permission will be chosen, which is not the optimal policy for the supply chain.*

D. Data Governance: Model

D.1. A Serial Supply Chain

In a serial supply chain, the quality of traceability data is determined by the upstream supplier. The downstream supplier does not have any incentive to incur additional cost to improve data quality because his chance of receiving the wholesale price payment from the buyer is not affected by the quality of data recorded in the blockchain (since he is only paid if the end product is non-defective). The game now consists of two stages. The first is the blockchain implementation stage, in which the upstream supplier chooses data quality α. The second is the quality contracting stage, in which the upstream supplier can prove that he is not the defect-causing supplier with probability α when he is non-defective himself. Hence, the buyer's contracting problem is formulated as

$$
\begin{aligned}
\max_{w_1}\quad & \pi_B(w_1|\tilde{q}_1(w_1,\tilde{w}_2(w_1)),\tilde{q}_2(w_1,\tilde{w}_2(w_1))) = p\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(w_1,\tilde{w}_2(w_1)) \\
& - l\big[1-\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(w_1,\tilde{w}_2(w_1))\big] - w_1\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(w_1,\tilde{w}_2(w_1)) \\
\text{s.t.}\quad & \begin{cases} \pi_{S_1}(\tilde{w}_2(w_1),\tilde{q}_1(w_1,\tilde{w}_2(w_1))|w_1,\tilde{q}_2(w_1,\tilde{w}_2(w_1))) \geqslant 0, & (\text{IR}_1) \\ \tilde{w}_2(w_1) = \arg\max\limits_{w_2}\ \pi_{S_1}(w_2,\tilde{q}_1(w_1,w_2)|w_1,\tilde{q}_2(w_1,w_2)) & \\ \quad \text{s.t.} \begin{cases} \pi_{S_2}(\tilde{q}_2(w_1,w_2)|w_2,\tilde{q}_1(w_1,w_2)) \geqslant 0, & (\text{IR}_2) \\ \tilde{q}_1(w_1,w_2) = \arg\max\limits_{q_1}\ \pi_{S_1}(w_2,q_1|w_1,q_2), & (\text{IC}_1) \\ \tilde{q}_2(w_1,w_2) = \arg\max\limits_{q_2}\ \pi_{S_2}(q_2|w_2,q_1), & (\text{IC}_2) \end{cases} \end{cases}
\end{aligned}
\tag{D.1}
$$

where $\pi_{S_1}(w_2,q_1|w_1,q_2) = w_1q_1q_2 - C(q_1) - w_2\big[q_1q_2 + \alpha q_2(1-q_1)\big]$ and $\pi_{S_2}(q_2|w_2,q_1) = w_2\big[q_1q_2 + \alpha q_2(1-q_1)\big] - C(q_2) - G(\alpha)$.

D.2. A Parallel Supply Chain

In a parallel supply chain, the quality of traceability data is determined by both suppliers. Since the two suppliers are symmetric, we focus on the case where they choose the same level of data quality. The game now consists of two stages. The first is the blockchain implementation stage, in which the suppliers choose data quality α. The second is the quality contracting stage, in which a supplier can prove that he is not the defect-causing supplier with probability α when he is non-defective himself and correspondingly, the buyer can recall only the defective products from the market. Hence, the buyer's contracting problem is formulated as

$$\begin{aligned}\max_{\mathbf{w}} \quad & \pi_B(\mathbf{w}|\tilde{\mathbf{q}}(\mathbf{w})) = p\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) - l\left[\sum_{i=1}^{2}\tilde{q}_i(\mathbf{w})\left[1-\tilde{q}_{-i}(\mathbf{w})\right](1-\alpha) + \prod_{i=1}^{2}\left[1-\tilde{q}_i(\mathbf{w})\right]\right] \\ & + \frac{1}{2}(p-l)\sum_{i=1}^{2}\tilde{q}_i(\mathbf{w})\left[1-\tilde{q}_{-i}(\mathbf{w})\right]\alpha - \left(\sum_{i=1}^{2} w_i\right)\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) - \sum_{i=1}^{2} w_i\alpha\tilde{q}_i(\mathbf{w})\left[1-\tilde{q}_{-i}(\mathbf{w})\right] \qquad \text{(D.2)} \\ \text{s.t.} \quad & \begin{cases} \pi_{S_i}(\tilde{q}_i(\mathbf{w})|w_i,\tilde{q}_{-i}(\mathbf{w})) \geqslant 0, i\in\{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(\mathbf{w}) = \arg\max_{q_i} \ \pi_{S_i}(q_i|w_i,q_{-i}), i\in\{1,2\} & (\text{IC}_i) \end{cases}\end{aligned}$$

where $\pi_{S_i}(q_i|w_i,q_{-i}) = w_i\left[q_iq_{-i} + \alpha q_i(1-q_{-i})\right] - C(q_i) - G(\alpha)$ for $i\in\{1,2\}$.

E. Limited Liability of Downstream Supplier

E.1. Model

In the main model, we assume that in a serial supply chain with traceability, the downstream supplier might need to pay the upstream supplier even if he does not receive any payment from the buyer. This occurs when the quality outcome up to the upstream supplier is non-defective while the quality outcome up to the downstream supplier is defective. However, in practice, the downstream supplier could have limited liability and may not pay the full wholesale price to the upstream supplier if he does not get paid by the buyer. In this extension, we incorporate the downstream supplier's limited liability constraint into analysis and assume that the downstream supplier will pay at most $b>0$ to the upstream supplier if he receives no payment from the buyer. (Note that this constraint only affects the case with traceability because in the case without traceability, the downstream supplier will not pay the upstream supplier if he receives no payment.) In this setting, the buyer's contracting problem in a serial supply chain with traceability is formulated as

$$\begin{aligned}\max_{w_1} \quad & \pi_B(w_1|\tilde{q}_1(w_1,\tilde{w}_2(w_1)),\tilde{q}_2(w_1,\tilde{w}_2(w_1))) = p\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(w_1,\tilde{w}_2(w_1)) \\ & \quad - l\left[1-\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(w_1,\tilde{w}_2(w_1))\right] - w_1\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(w_1,\tilde{w}_2(w_1)) \\ \text{s.t.} \quad & \begin{cases} \pi_{S_1}(\tilde{w}_2(w_1),\tilde{q}_1(w_1,\tilde{w}_2(w_1))|w_1,\tilde{q}_2(w_1,\tilde{w}_2(w_1))) \geqslant 0, & (\text{IR}_1) \\ \tilde{w}_2(w_1) = \arg\max_{w_2} \ \pi_{S_1}(w_2,\tilde{q}_1(w_1,w_2)|w_1,\tilde{q}_2(w_1,w_2)) \\ \qquad \text{s.t.} \begin{cases} \pi_{S_2}(\tilde{q}_2(w_1,w_2)|w_2,q_1) \geqslant 0, & (\text{IR}_2) \\ \tilde{q}_1(w_1,w_2) = \arg\max_{q_1} \ \pi_{S_1}(w_2,q_1|w_1,q_2), & (\text{IC}_1) \\ \tilde{q}_2(w_1,w_2) = \arg\max_{q_2} \ \pi_{S_2}(q_2|w_2,q_1), & (\text{IC}_2) \end{cases} \end{cases}\end{aligned} \qquad \text{(E.1)}$$

where $\pi_{S_1}(w_2,q_1|w_1,q_2) = w_1q_1q_2 - C(q_1) - w_2q_1q_2 - \min\{w_2,b\}q_2(1-q_1)$ and $\pi_{S_2}(q_2|w_2,q_1) = w_2q_1q_2 + \min\{w_2,b\}q_2(1-q_1) - C(q_2)$.

E.2. Equilibrium Analysis and Results

We confirm that our main insights regarding the impact of traceability carry through. In particular, when the downstream supplier's liability is not too limited (i.e., when b is sufficiently large), traceability always improves product quality and all firms' profits, and traceability creates value by mitigating double moral hazard; whereas when the downstream supplier's liability is extremely limited (i.e., when $b=0$), traceability has no impact on product quality or any firm's profit (see Proposition E.1 and Theorem E.1). We also verify that our main findings carry over when b is moderate (see Figures E.1 and E.2). Moreover, we find that as the downstream supplier's liability becomes less limited (i.e., as b increases), traceability creates higher values to the buyer, the suppliers, and the entire supply chain (see Figures E.1 and E.2).

Proposition E.1 (Equilibrium with Traceability in a Serial Supply Chain). *In a serial supply chain with traceability, when the downstream supplier has limited liability, there exists a threshold* $\bar{b}=\left[2(p+l)\right]^{\frac{\gamma-1}{\gamma-2}}\left(\frac{1}{\theta}\right)^{\frac{1}{\gamma-2}}\left(\frac{1}{\gamma}\right)^{\frac{2\gamma^2-2\gamma+1}{\gamma(\gamma-2)}}$ *such that*

(a) if $b\geqslant\bar{b}$, the buyer offers wholesale price $w_1^{T\ddagger}=\frac{2(p+l)}{\gamma}$ to the downstream supplier, the downstream supplier offers wholesale price $w_2^{T\ddagger}=\left[2(p+l)\right]^{\frac{\gamma-1}{\gamma-2}}\left(\frac{1}{\theta}\right)^{\frac{1}{\gamma-2}}\left(\frac{1}{\gamma}\right)^{\frac{2\gamma^2-2\gamma+1}{\gamma(\gamma-2)}}$ to the upstream supplier, and the downstream and the upstream suppliers' quality levels are $q_1^{T\ddagger}=\left[\frac{2(p+l)}{\theta\gamma^{2+\frac{1}{\gamma}}}\right]^{\frac{1}{\gamma-2}}$ and $q_2^{T\ddagger}=\left[\frac{2(p+l)}{\theta\gamma^{3-\frac{1}{\gamma}}}\right]^{\frac{1}{\gamma-2}}$, respectively;

(b) if $b=0$, the buyer offers wholesale price $w_1^{T\ddagger}=\frac{2(p+l)}{\gamma}$ to the downstream supplier, the downstream supplier offers wholesale price $w_2^{T\ddagger}=\frac{2(p+l)}{\gamma^2}$ to the upstream supplier, and the downstream and the upstream suppliers' quality levels are $q_1^{T\ddagger}=\left[\frac{2(p+l)(\gamma-1)^{\frac{\gamma-1}{\gamma}}}{\theta\gamma^3}\right]^{\frac{1}{\gamma-2}}$ and $q_2^{T\ddagger}=\left[\frac{2(p+l)(\gamma-1)^{\frac{1}{\gamma}}}{\theta\gamma^3}\right]^{\frac{1}{\gamma-2}}$, respectively.

Theorem E.1 (Comparison of Equilibria in a Serial Supply Chain). *In a serial supply chain, when the downstream supplier has limited liability,*

(a) if $b\geqslant\bar{b}$, traceability always improves product quality and all firms' profits;

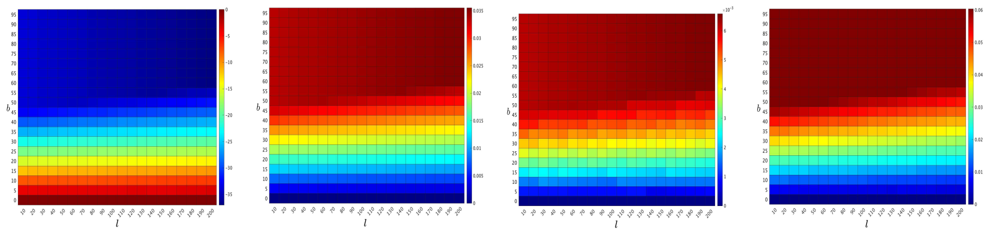
(b) if $b=0$, traceability has no impact on product quality or any firm's profit.

F. Downstream Supplier's Use of Traceability Information Upon Receiving the Product

F.1. Model

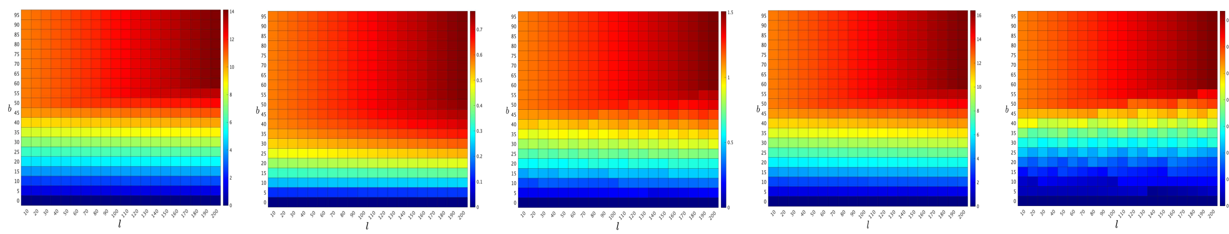
In the main model, we assume that in a serial supply chain with traceability, the traceability information is used to decide which supplier should be paid after the end product is sold. In this extension, we consider an alternative way for the traceability information to be utilized. That is, the downstream supplier uses the traceability information to investigate the quality of the product delivered by the upstream supplier and pays the upstream supplier accordingly upon receiving

Figure E.1 **Comparison of Contracts in a Serial Supply Chain ($p = 1000$, $\theta = 300$, $\gamma = 5$)**



(a) $w_2^{T\ddagger} - w_2^{N\ddagger}$ (b) $q_1^{T\ddagger} - q_1^{N\ddagger}$ (c) $q_2^{T\ddagger} - q_2^{N\ddagger}$ (d) $q_1^{T\ddagger}/q_2^{T\ddagger} - q_1^{N\ddagger}/q_2^{N\ddagger}$

Figure E.2 **Comparison of Firm Profits in a Serial Supply Chain ($p = 1000$, $\theta = 300$, $\gamma = 5$)**



(a) $\pi_B^{T\ddagger} - \pi_B^{N\ddagger}$ (b) $\pi_{S_1}^{T\ddagger} - \pi_{S_1}^{N\ddagger}$ (c) $\pi_{S_2}^{T\ddagger} - \pi_{S_2}^{N\ddagger}$ (d) $\pi_{SC}^{T\ddagger} - \pi_{SC}^{N\ddagger}$ (e) $\left(\pi_{S_2}^{T\ddagger} - \pi_{S_2}^{N\ddagger}\right) - \left(\pi_{S_1}^{T\ddagger} - \pi_{S_1}^{N\ddagger}\right)$

the product. Specifically, if the product delivered by the upstream supplier is non-defective, the downstream supplier pays w_2 to the upstream supplier and then produces the end product; otherwise, the downstream supplier returns the incoming product to the upstream supplier without any payment (in which case the downstream supplier does not produce the end product and no market loss will be incurred). In this setting, the buyer's contracting problem in a serial supply chain with traceability is formulated as

$$\begin{aligned}
\max_{w_1} \quad & \pi_B(w_1|\tilde{q}_1(w_1,\tilde{w}_2(w_1)),\tilde{q}_2(\tilde{w}_2(w_1))) = p\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1)) \\
& - l\big[1-\tilde{q}_1(w_1,\tilde{w}_2(w_1))\big]\tilde{q}_2(\tilde{w}_2(w_1)) - w_1\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1)) \\
\text{s.t.} \quad & \begin{cases} \pi_{S_1}(\tilde{w}_2(w_1),\tilde{q}_1(w_1,\tilde{w}_2(w_1))|w_1,\tilde{q}_2(\tilde{w}_2(w_1))) \geqslant 0, & (\text{IR}_1) \\ \tilde{w}_2(w_1) = \arg\max\limits_{w_2} \ \pi_{S_1}(w_2,\tilde{q}_1(w_1,w_2)|w_1,\tilde{q}_2(w_2)) \end{cases} \\
& \qquad \text{s.t.} \begin{cases} \pi_{S_2}(\tilde{q}_2(w_2)|w_2) \geqslant 0, & (\text{IR}_2) \\ \tilde{q}_1(w_1,w_2) = \arg\max\limits_{q_1} \ \pi_{S_1}(w_2,q_1|w_1,q_2), & (\text{IC}_1) \\ \tilde{q}_2(w_2) = \arg\max\limits_{q_2} \ \pi_{S_2}(q_2|w_2), & (\text{IC}_2) \end{cases}
\end{aligned} \tag{F.1}$$

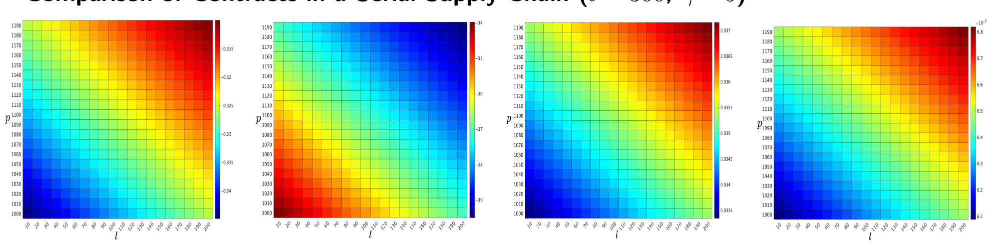
where $\pi_{S_1}(w_2,q_1|w_1,q_2) = w_1q_1q_2 - C(q_1) - w_2q_2$ and $\pi_{S_2}(q_2|w_2) = w_2q_2 - C(q_2)$.

F.2. Equilibrium Analysis and Results

We confirm that our main insights regarding the impact of traceability carry through. In particular, we find that traceability always improves product quality and all firms' profits in a serial supply chain (see Figures F.1 and F.2), which is consistent with the main model. Moreover, traceability still always increases the discrepancy between the two suppliers' quality levels (i.e., $q_1^{T\ddagger}/q_2^{T\ddagger} = \gamma^{\frac{1}{\gamma}} > (\gamma-1)^{\frac{1}{\gamma}} = q_1^{N\ddagger}/q_2^{N\ddagger}$; see Propositions F.1 and 1). Our finding indicates that the driving force behind the impact of traceability in a serial supply chain remains unchanged even if the traceability information is used by the downstream supplier upon receiving the product. This is because the upstream supplier will receive the payment from the downstream supplier as long as he is non-defective himself regardless of whether he is paid before or after the end product is produced and sold. Hence, traceability can still help disentangle the responsibility of the upstream supplier from that of the downstream supplier and correspondingly mitigate the double moral hazard.

Proposition F.1 (Equilibrium with Traceability in a Serial Supply Chain). *In a serial supply chain with traceability, when the downstream supplier uses the traceability information to pay the upstream supplier upon receiving the product, there exists a unique equilibrium such that the buyer offers wholesale price $w_1^{T\ddagger}$ to the downstream supplier, the downstream supplier offers wholesale price $w_2^{T\ddagger} = \left[\frac{\left(w_1^{T\ddagger}\right)^{\gamma(\gamma-1)}}{\theta^\gamma \gamma^{\gamma^2-\gamma+1}}\right]^{\frac{1}{\gamma(\gamma-2)}}$ to the upstream supplier, and the downstream and the upstream suppliers' quality levels are $q_1^{T\ddagger} = \left[\frac{\left(w_1^{T\ddagger}\right)^{\gamma}}{\theta^\gamma \gamma^{\gamma+1}}\right]^{\frac{1}{\gamma(\gamma-2)}}$ and $q_2^{T\ddagger} = \left[\frac{\left(w_1^{T\ddagger}\right)^{\gamma}}{\theta^\gamma \gamma^{2\gamma-1}}\right]^{\frac{1}{\gamma(\gamma-2)}}$, respectively, where $w_1^{T\ddagger}$ satisfies $2(p+l) - \gamma w_1^{T\ddagger} = l\left[\frac{\theta^\gamma \gamma^{\gamma+1}}{\left(w_1^{T\ddagger}\right)^{\gamma}}\right]^{\frac{1}{\gamma(\gamma-2)}}$. Moreover, $q_1^{T\ddagger}/q_2^{T\ddagger} = \gamma^{\frac{1}{\gamma}} > 1$.*

Figure F.1 Comparison of Contracts in a Serial Supply Chain ($\theta = 300$, $\gamma = 5$)



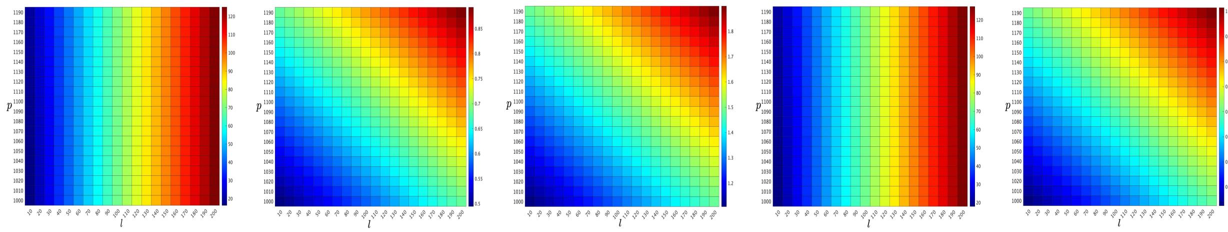
(a) $w_1^{T\ddagger} - w_1^{N\ddagger}$ (b) $w_2^{T\ddagger} - w_2^{N\ddagger}$ (c) $q_1^{T\ddagger} - q_1^{N\ddagger}$ (d) $q_2^{T\ddagger} - q_2^{N\ddagger}$

G. An Assembly Supply Chain

G.1. Model

In this section, we consider an assembly supply chain that consists of a buyer and two suppliers (see Figure G.1). Different from our parallel supply chain, the buyer procures different components from the two suppliers and assembles the components into the end product. The quality level of the end product is jointly determined by the quality level of both suppliers. That is, the end product

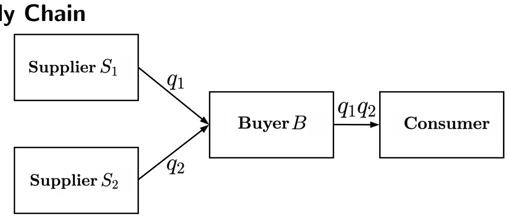
Figure F.2 Comparison of Firm Profits in a Serial Supply Chain ($\theta = 300$, $\gamma = 5$)



(a) $\pi_B^{T\ddagger} - \pi_B^{N\ddagger}$ (b) $\pi_{S_1}^{T\ddagger} - \pi_{S_1}^{N\ddagger}$ (c) $\pi_{S_2}^{T\ddagger} - \pi_{S_2}^{N\ddagger}$ (d) $\pi_{SC}^{T\ddagger} - \pi_{SC}^{N\ddagger}$ (e) $\left(\pi_{S_2}^{T\ddagger} - \pi_{S_2}^{N\ddagger}\right) - \left(\pi_{S_1}^{T\ddagger} - \pi_{S_1}^{N\ddagger}\right)$

is non-defective with probability q_1q_2, and defective with probability $1 - q_1q_2$. Traceability enables the buyer to identify the defect-causing supplier once a defect occurs.

Figure G.1 An Assembly Supply Chain



The buyer's contracting problem in an assembly supply chain without traceability is formulated as

$$\begin{aligned} \max_{\mathbf{w}} \quad & \pi_B(\mathbf{w}|\tilde{\mathbf{q}}(\mathbf{w})) = p\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) - l\left[1 - \prod_{i=1}^{2}\tilde{q}_i(\mathbf{w})\right] - \left(\sum_{i=1}^{2} w_i\right)\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) \\ \text{s.t.} \quad & \begin{cases} \pi_{S_i}(\tilde{q}_i(\mathbf{w})|w_i, \tilde{q}_{-i}(\mathbf{w})) \geqslant 0, i \in \{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(\mathbf{w}) = \underset{q_i}{\text{argmax}} \ \ \pi_{S_i}(q_i|w_i, q_{-i}), i \in \{1,2\} & (\text{IC}_i) \end{cases} \end{aligned} \tag{G.1}$$

where $\pi_{S_i}(q_i|w_i, q_{-i}) = w_iq_iq_{-i} - C(q_i)$ for $i \in \{1,2\}$.

The buyer's contracting problem in an assembly supply chain with traceability is formulated as

$$\begin{aligned} \max_{\mathbf{w}} \quad & \pi_B(\mathbf{w}|\tilde{q}_1(w_1), \tilde{q}_2(w_2)) = p\prod_{i=1}^{2}\tilde{q}_i(w_i) - l\left[1 - \prod_{i=1}^{2}\tilde{q}_i(w_i)\right] - \sum_{i=1}^{2} w_i\tilde{q}_i(w_i) \\ \text{s.t.} \quad & \begin{cases} \pi_{S_i}(\tilde{q}_i(w_i)|w_i) \geqslant 0, i \in \{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(w_i) = \underset{q_i}{\text{argmax}} \ \ \pi_{S_i}(q_i|w_i), i \in \{1,2\} & (\text{IC}_i) \end{cases} \end{aligned} \tag{G.2}$$

where $\pi_{S_i}(q_i|w_i) = w_iq_i - C(q_i)$ for $i \in \{1,2\}$.

G.2. Equilibrium Analysis and Results

Proposition G.1 (Equilibrium without Traceability in an Assembly Supply Chain). *In an assembly supply chain without traceability, there exists a unique equilibrium such that the* *buyer offers wholesale price* $w_i^{N\star}=\frac{p+l}{\gamma}$ *to supplier* $i\in\{1,2\}$*, and supplier* i *chooses quality level* $q_i^{N\star}=\left(\frac{p+l}{\theta\gamma^2}\right)^{\frac{1}{\gamma-2}}$.

Proposition G.2 (Equilibrium with Traceability in an Assembly Supply Chain). *In an assembly supply chain with traceability, there exists a unique equilibrium such that the buyer offers wholesale price* $w_i^{T\star}=(p+l)^{\frac{\gamma-1}{\gamma-2}}\left(\frac{1}{\theta}\right)^{\frac{1}{\gamma-2}}\left(\frac{1}{\gamma}\right)^{\frac{\gamma}{\gamma-2}}$ *to supplier* $i\in\{1,2\}$*, and supplier* i *chooses quality level* $q_i^{T\star}=\left(\frac{p+l}{\theta\gamma^2}\right)^{\frac{1}{\gamma-2}}$.

Theorem G.1 (Comparison of Equilibria in an Assembly Supply Chain). *In an assembly supply chain, traceability decreases the wholesale prices, but does not change the suppliers' quality levels, the buyer's or the suppliers' expected profits, or the total supply chain profit.*

H. Buyer's Product Inspection

H.1. Model

In the main model, we focus on the scenario in which the buyer sells the product to the market without inspecting the quality. This could correspond to cases where inspection is infeasible or prohibitively costly. However, in other cases, the buyer may inspect the product before selling to the market (e.g., Balachandran and Radhakrishnan 2005, Hwang et al. 2006, Lee and Li 2018). In this extension, we study a setting in which the buyer chooses the optimal inspection level, $\beta\in[0,1]$, which represents the probability that a defective product is identified by the buyer and returned to the supplier without payment. Consistent with the literature, we assume that the buyer's inspection cost is $I(\beta)=\frac{1}{2}\mu\beta^2$, where $\mu>0$ measures the efficiency of product inspection.

H.1.1. A Serial Supply Chain. When the buyer inspects the product before selling to the market and chooses the inspection level β, the buyer's contracting problem in a serial supply chain without traceability is formulated as

$$
\begin{aligned}
\max_{w_1,\beta}\quad & \pi_B(w_1,\beta|\tilde{q}_1(w_1,\tilde{w}_2(w_1)),\tilde{q}_2(w_1,\tilde{w}_2(w_1)))\\
&=p\prod_{i=1}^{2}\tilde{q}_i(w_1,\tilde{w}_2(w_1))-l\left[1-\prod_{i=1}^{2}\tilde{q}_i(w_1,\tilde{w}_2(w_1))\right](1-\beta)-w_1\prod_{i=1}^{2}\tilde{q}_i(w_1,\tilde{w}_2(w_1))-I(\beta)\\
\text{s.t.}\quad & \begin{cases}\pi_{S_1}(\tilde{w}_2(w_1),\tilde{q}_1(w_1,\tilde{w}_2(w_1))|w_1,\tilde{q}_2(w_1,\tilde{w}_2(w_1)))\geqslant 0, & (\text{IR}_1)\\
\tilde{w}_2(w_1)=\arg\max_{w_2}\ \pi_{S_1}(w_2,\tilde{q}_1(w_1,w_2)|w_1,\tilde{q}_2(w_1,w_2))\\
\quad\text{s.t.}\begin{cases}\pi_{S_2}(\tilde{q}_2(w_1,w_2)|w_2,\tilde{q}_1(w_1,w_2))\geqslant 0, & (\text{IR}_2)\\
\tilde{q}_1(w_1,w_2)=\arg\max_{q_1}\ \pi_{S_1}(w_2,q_1|w_1,q_2), & (\text{IC}_1)\\
\tilde{q}_2(w_1,w_2)=\arg\max_{q_2}\ \pi_{S_2}(q_2|w_2,q_1), & (\text{IC}_2)\end{cases}\end{cases}
\end{aligned}
\tag{H.1}
$$

where $\pi_{S_1}(w_2,q_1|w_1,q_2)=w_1q_1q_2-C(q_1)-w_2q_1q_2$ and $\pi_{S_2}(q_2|w_2,q_1)=w_2q_1q_2-C(q_2)$.

The buyer's contracting problem in a serial supply chain with traceability is formulated as

$$
\begin{aligned}
\max_{w_1,\beta}\quad & \pi_B(w_1,\beta|\tilde{q}_1(w_1,\tilde{w}_2(w_1)),\tilde{q}_2(\tilde{w}_2(w_1))) = p\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1)) \\
& - l\big[1-\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1))\big](1-\beta) - w_1\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1)) - I(\beta) \\
\text{s.t.}\quad & \begin{cases} \pi_{S_1}(\tilde{w}_2(w_1),\tilde{q}_1(w_1,\tilde{w}_2(w_1))|w_1,\tilde{q}_2(\tilde{w}_2(w_1))) \geqslant 0, & (\text{IR}_1) \\ \tilde{w}_2(w_1) = \arg\max_{w_2}\ \pi_{S_1}(w_2,\tilde{q}_1(w_1,w_2)|w_1,\tilde{q}_2(w_2)) \end{cases} \\
& \qquad \text{s.t.} \begin{cases} \pi_{S_2}(\tilde{q}_2(w_2)|w_2) \geqslant 0, & (\text{IR}_2) \\ \tilde{q}_1(w_1,w_2) = \arg\max_{q_1}\ \pi_{S_1}(w_2,q_1|w_1,q_2), & (\text{IC}_1) \\ \tilde{q}_2(w_2) = \arg\max_{q_2}\ \pi_{S_2}(q_2|w_2), & (\text{IC}_2) \end{cases}
\end{aligned} \tag{H.2}
$$

where $\pi_{S_1}(w_2,q_1|w_1,q_2) = w_1q_1q_2 - C(q_1) - w_2q_2$ and $\pi_{S_2}(q_2|w_2) = w_2q_2 - C(q_2)$.

H.1.2. A Parallel Supply Chain. When the buyer inspects the product before selling to the market and chooses the inspection level β, the buyer's contracting problem in a parallel supply chain without traceability is formulated as

$$
\begin{aligned}
\max_{\mathbf{w},\beta}\quad & \pi_B(\mathbf{w},\beta|\tilde{\mathbf{q}}(\mathbf{w})) = p\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) - l\left[1-\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w})\right](1-\beta) - \left(\sum_{i=1}^{2}w_i\right)\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) - I(\beta) \\
\text{s.t.}\quad & \begin{cases} \pi_{S_i}(\tilde{q}_i(\mathbf{w})|w_i,\tilde{q}_{-i}(\mathbf{w})) \geqslant 0, i\in\{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(\mathbf{w}) = \arg\max_{q_i}\ \pi_{S_i}(q_i|w_i,q_{-i}), i\in\{1,2\} & (\text{IC}_i) \end{cases}
\end{aligned} \tag{H.3}
$$

where $\pi_{S_i}(q_i|w_i,q_{-i}) = w_iq_iq_{-i} - C(q_i)$ for $i\in\{1,2\}$.

The buyer's contracting problem in a parallel supply chain with traceability is formulated as

$$
\begin{aligned}
\max_{\mathbf{w},\beta}\quad & \pi_B(\mathbf{w},\beta|\tilde{q}_1(w_1),\tilde{q}_2(w_2)) = \frac{1}{2}p\sum_{i=1}^{2}\tilde{q}_i(w_i) - \frac{1}{2}l\sum_{i=1}^{2}\left[1-\tilde{q}_i(w_i)\right](1-\beta) - \sum_{i=1}^{2}w_i\tilde{q}_i(w_i) - I(\beta) \\
\text{s.t.}\quad & \begin{cases} \pi_{S_i}(\tilde{q}_i(w_i)|w_i) \geqslant 0, i\in\{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(w_i) = \arg\max_{q_i}\ \pi_{S_i}(q_i|w_i), i\in\{1,2\} & (\text{IC}_i) \end{cases}
\end{aligned} \tag{H.4}
$$

where $\pi_{S_i}(q_i|w_i) = w_iq_i - C(q_i)$ for $i\in\{1,2\}$.

H.2. Equilibrium Analysis and Results

We show that the equilibrium outcomes remain qualitatively unchanged and our main insights regarding the impact of traceability carry through. For example, in a serial supply chain, with traceability, the downstream supplier always invests disproportionately more than the upstream supplier compared to the case without traceability (see Propositions H.1 and H.2). Besides, as Figures H.1 and H.2 illustrate, traceability always improves the product quality and all firms' profits in a serial supply chain. By contrast, in a parallel supply chain, traceability can improve the buyer's profit while reducing the suppliers' profits and the product quality (see Figures H.3 and H.4). Furthermore, we find that regardless of the supply chain structure, the buyer always chooses a lower inspection level with traceability than without (see Figures H.1(e) and H.3(c)).

Hence, in both serial and parallel supply chains, traceability and product inspection can work as partially *substitutable* instruments for quality management. Finally, we can also see that as product inspection becomes more costly (i.e., as μ increases), traceability creates higher values to all firms in a serial supply chain (see Figure H.2), whereas it creates higher values to the buyer and the supply chain while creating lower (or even no) values to the suppliers in a parallel supply chain (see Figure H.4).

Proposition H.1 (Equilibrium without Traceability in a Serial Supply Chain). *When the buyer inspects the product before selling to the market, in a serial supply chain without traceability, there exists a unique equilibrium such that the buyer chooses inspection level* $\beta^{N\ddagger}$ *that satisfies* $(\gamma-1)^{\frac{1}{\gamma-2}}\left[\frac{2\left[p+l\left(1-\beta^{N\ddagger}\right)\right]}{\theta\gamma^3}\right]^{\frac{2}{\gamma-2}}=1-\frac{\mu\beta^{N\ddagger}}{l}$ *and offers wholesale price* $w_1^{N\ddagger}=\frac{2\left[p+l\left(1-\beta^{N\ddagger}\right)\right]}{\gamma}$ *to the downstream supplier, the downstream supplier offers wholesale price* $w_2^{N\ddagger}=\frac{2\left[p+l\left(1-\beta^{N\ddagger}\right)\right]}{\gamma^2}$ *to the upstream supplier, and the downstream and the upstream suppliers' quality levels are* $q_1^{N\ddagger}=\left[\frac{2\left[p+l\left(1-\beta^{N\ddagger}\right)\right](\gamma-1)^{\frac{\gamma-1}{\gamma}}}{\theta\gamma^3}\right]^{\frac{1}{\gamma-2}}$ *and* $q_2^{N\ddagger}=\left[\frac{2\left[p+l\left(1-\beta^{N\ddagger}\right)\right](\gamma-1)^{\frac{1}{\gamma}}}{\theta\gamma^3}\right]^{\frac{1}{\gamma-2}}$*, respectively. Moreover,* $w_1^{N\ddagger}/w_2^{N\ddagger}=\gamma\geqslant 2$ *and* $q_1^{N\ddagger}/q_2^{N\ddagger}=(\gamma-1)^{\frac{1}{\gamma}}\geqslant 1$.

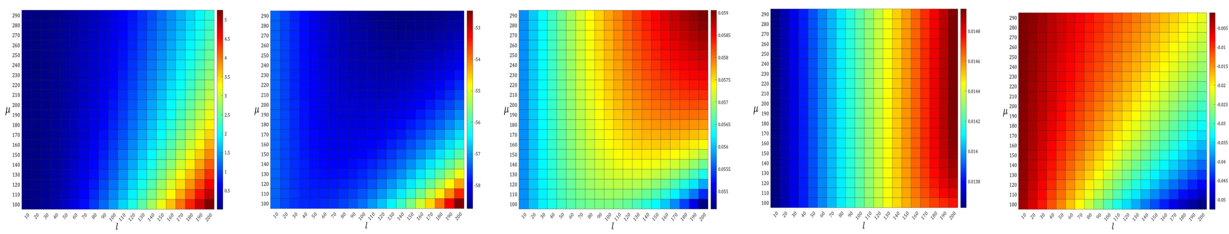
Proposition H.2 (Equilibrium with Traceability in a Serial Supply Chain). *When the buyer inspects the product before selling to the market, in a serial supply chain with traceability, there exists a unique equilibrium such that the buyer chooses inspection level* $\beta^{T\ddagger}$ *that satisfies* $\left[\frac{2\left[p+l\left(1-\beta^{T\ddagger}\right)\right]}{\theta\gamma^{\frac{5}{2}}}\right]^{\frac{2}{\gamma-2}}=1-\frac{\mu\beta^{T\ddagger}}{l}$ *and offers wholesale price* $w_1^{T\ddagger}=\frac{2\left[p+l\left(1-\beta^{T\ddagger}\right)\right]}{\gamma}$ *to the downstream supplier, the downstream supplier offers wholesale price* $w_2^{T\ddagger}=\left[2\left[p+l\left(1-\beta^{T\ddagger}\right)\right]\right]^{\frac{\gamma-1}{\gamma-2}}\left(\frac{1}{\theta}\right)^{\frac{1}{\gamma-2}}\left(\frac{1}{\gamma}\right)^{\frac{2\gamma^2-2\gamma+1}{\gamma(\gamma-2)}}$ *to the upstream supplier, and the downstream and the upstream suppliers' quality levels are* $q_1^{T\ddagger}=\left[\frac{2\left[p+l\left(1-\beta^{T\ddagger}\right)\right]}{\theta\gamma^{2+\frac{1}{\gamma}}}\right]^{\frac{1}{\gamma-2}}$ *and* $q_2^{T\ddagger}=\left[\frac{2\left[p+l\left(1-\beta^{T\ddagger}\right)\right]}{\theta\gamma^{3-\frac{1}{\gamma}}}\right]^{\frac{1}{\gamma-2}}$*, respectively. Moreover,* $w_1^{T\ddagger}/w_2^{T\ddagger}=\gamma/q_1^{T\ddagger}>\gamma$ *and* $q_1^{T\ddagger}/q_2^{T\ddagger}=\gamma^{\frac{1}{\gamma}}>1$.

Proposition H.3 (Equilibrium without Traceability in a Parallel Supply Chain). *When the buyer inspects the product before selling to the market, in a parallel supply chain without traceability, there exists a unique equilibrium such that the buyer chooses inspection level* $\beta^{N\dagger}$ *that satisfies* $\left[\frac{p+l\left(1-\beta^{N\dagger}\right)}{\theta\gamma^2}\right]^{\frac{2}{\gamma-2}}=1-\frac{\mu\beta^{N\dagger}}{l}$ *and offers wholesale price* $w_i^{N\dagger}=\frac{p+l\left(1-\beta^{N\dagger}\right)}{\gamma}$ *to supplier* $i\in\{1,2\}$*, and supplier* i *chooses quality level* $q_i^{N\dagger}=\left[\frac{p+l\left(1-\beta^{N\dagger}\right)}{\theta\gamma^2}\right]^{\frac{1}{\gamma-2}}$.

Proposition H.4 (Equilibrium with Traceability in a Parallel Supply Chain). *When the buyer inspects the product before selling to the market, in a parallel supply chain with traceability, there exists a unique equilibrium such that the buyer chooses inspection level* $\beta^{T\dagger}$

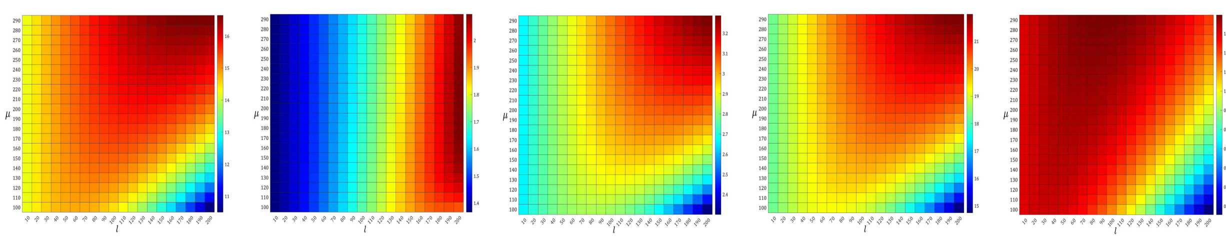
that satisfies $\left[\frac{p+l\left(1-\beta^{T\dagger}\right)}{2\theta\gamma^2}\right]^{\frac{1}{\gamma-1}} = 1 - \frac{\mu\beta^{T\dagger}}{l}$ *and offers wholesale price* $w_i^{T\dagger} = \frac{p+l\left(1-\beta^{T\dagger}\right)}{2\gamma}$ *to supplier* $i \in \{1,2\}$, *and supplier* i *chooses quality level* $q_i^{T\dagger} = \left[\frac{p+l\left(1-\beta^{T\dagger}\right)}{2\theta\gamma^2}\right]^{\frac{1}{\gamma-1}}$.

Figure H.1 Comparison of Contracts in a Serial Supply Chain ($p = 1000$, $\theta = 300$, $\gamma = 5$)



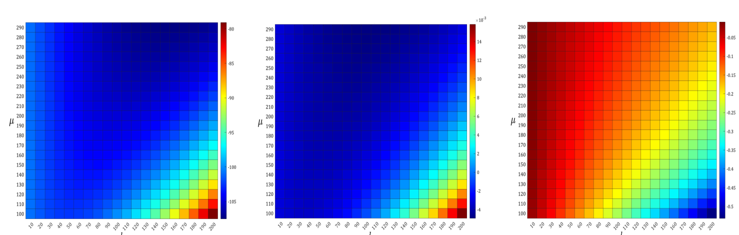
(a) $w_1^{T\ddagger} - w_1^{N\ddagger}$ (b) $w_2^{T\ddagger} - w_2^{N\ddagger}$ (c) $q_1^{T\ddagger} - q_1^{N\ddagger}$ (d) $q_2^{T\ddagger} - q_2^{N\ddagger}$ (e) $\beta^{T\ddagger} - \beta^{N\ddagger}$

Figure H.2 Comparison of Firm Profits in a Serial Supply Chain ($p = 1000$, $\theta = 300$, $\gamma = 5$)



(a) $\pi_B^{T\ddagger} - \pi_B^{N\ddagger}$ (b) $\pi_{S_1}^{T\ddagger} - \pi_{S_1}^{N\ddagger}$ (c) $\pi_{S_2}^{T\ddagger} - \pi_{S_2}^{N\ddagger}$ (d) $\pi_{SC}^{T\ddagger} - \pi_{SC}^{N\ddagger}$ (e) $\left(\pi_{S_2}^{T\ddagger} - \pi_{S_2}^{N\ddagger}\right) - \left(\pi_{S_1}^{T\ddagger} - \pi_{S_1}^{N\ddagger}\right)$

Figure H.3 Comparison of Contracts in a Parallel Supply Chain ($p = 1000$, $\theta = 300$, $\gamma = 5$)



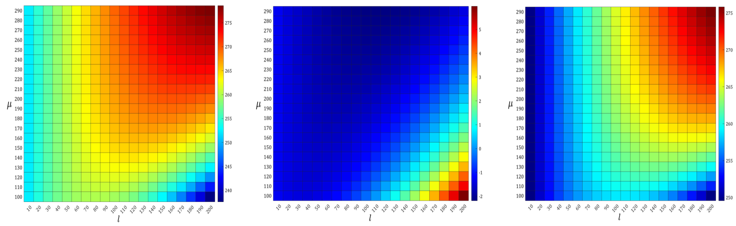
(a) $w_i^{T\dagger} - w_i^{N\dagger}$ (b) $q_i^{T\dagger} - q_i^{N\dagger}$ (c) $\beta^{T\dagger} - \beta^{N\dagger}$

I. Suppliers' Exogenous Loss

I.1. Model

Throughout the paper, we assume that only the buyer will incur an exogenous loss when a defect occurs in the end market. However, besides losing wholesale price payments, suppliers may also suffer from reputation damage and market loss (e.g., Plambeck and Taylor 2016). In this extension, we

Figure H.4 Comparison of Firm Profits in a Parallel Supply Chain ($p=1000$, $\theta=300$, $\gamma=5$)



(a) $\pi_B^{T\dagger}-\pi_B^{N\dagger}$ (b) $\pi_{S_i}^{T\dagger}-\pi_{S_i}^{N\dagger}$ (c) $\pi_{SC}^{T\dagger}-\pi_{SC}^{N\dagger}$

assume that the suppliers will incur an exogenous loss $l_s>0$ when a defect occurs. Correspondingly, Assumption 1 is replaced by the following:

Assumption I.1 (Existence of Interior Solution). $\theta>\frac{p+l+2l_s}{\gamma}$.

Moreover, we also assume in this extension that l_s is not prohibitively high in order not to over-complicate the model; otherwise, whether or not the suppliers' individual rationality constraints are binding simultaneously for the cases with and without traceability would need to be discussed, while the main insights would still carry through.

I.1.1. A Serial Supply Chain. When the suppliers incur a loss l_s under defect, the buyer's contracting problem in a serial supply chain without traceability is formulated as

$$\begin{aligned}
\max_{w_1}\quad & \pi_B(w_1|\tilde{q}_1(w_1,\tilde{w}_2(w_1)),\tilde{q}_2(w_1,\tilde{w}_2(w_1)))\\
&= p\prod_{i=1}^{2}\tilde{q}_i(w_1,\tilde{w}_2(w_1))-l\left[1-\prod_{i=1}^{2}\tilde{q}_i(w_1,\tilde{w}_2(w_1))\right]-w_1\prod_{i=1}^{2}\tilde{q}_i(w_1,\tilde{w}_2(w_1))\\
\text{s.t.}\quad & \begin{cases}\pi_{S_1}(\tilde{w}_2(w_1),\tilde{q}_1(w_1,\tilde{w}_2(w_1))|w_1,\tilde{q}_2(w_1,\tilde{w}_2(w_1)))\geqslant 0, & (\text{IR}_1)\\ \tilde{w}_2(w_1)=\arg\max\limits_{w_2}\ \pi_{S_1}(w_2,\tilde{q}_1(w_1,w_2)|w_1,\tilde{q}_2(w_1,w_2)) & \end{cases}\\
& \qquad \text{s.t.}\ \begin{cases}\pi_{S_2}(\tilde{q}_2(w_1,w_2)|w_2,\tilde{q}_1(w_1,w_2))\geqslant 0, & (\text{IR}_2)\\ \tilde{q}_1(w_1,w_2)=\arg\max\limits_{q_1}\ \pi_{S_1}(w_2,q_1|w_1,q_2), & (\text{IC}_1)\\ \tilde{q}_2(w_1,w_2)=\arg\max\limits_{q_2}\ \pi_{S_2}(q_2|w_2,q_1), & (\text{IC}_2)\end{cases}
\end{aligned}\tag{I.1}$$

where $\pi_{S_1}(w_2,q_1|w_1,q_2)=w_1q_1q_2-l_s(1-q_1q_2)-C(q_1)-w_2q_1q_2$ and $\pi_{S_2}(q_2|w_2,q_1)=w_2q_1q_2-l_s(1-q_1q_2)-C(q_2)$.

The buyer's contracting problem in a serial supply chain with traceability is formulated as

$$\begin{aligned}
\max_{w_1} \quad & \pi_B(w_1|\tilde{q}_1(w_1,\tilde{w}_2(w_1)),\tilde{q}_2(\tilde{w}_2(w_1))) = p\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1)) \\
& - l\big[1-\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1))\big] - w_1\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1)) \\
\text{s.t.} \quad & \begin{cases} \pi_{S_1}(\tilde{w}_2(w_1),\tilde{q}_1(w_1,\tilde{w}_2(w_1))|w_1,\tilde{q}_2(\tilde{w}_2(w_1))) \geqslant 0, & (\text{IR}_1) \\ \tilde{w}_2(w_1) = \arg\max\limits_{w_2} \; \pi_{S_1}(w_2,\tilde{q}_1(w_1,w_2)|w_1,\tilde{q}_2(w_2)) & \end{cases} \\
& \qquad \text{s.t.} \begin{cases} \pi_{S_2}(\tilde{q}_2(w_2)|w_2) \geqslant 0, & (\text{IR}_2) \\ \tilde{q}_1(w_1,w_2) = \arg\max\limits_{q_1} \; \pi_{S_1}(w_2,q_1|w_1,q_2), & (\text{IC}_1) \\ \tilde{q}_2(w_2) = \arg\max\limits_{q_2} \; \pi_{S_2}(q_2|w_2), & (\text{IC}_2) \end{cases}
\end{aligned} \tag{I.2}$$

where $\pi_{S_1}(w_2,q_1|w_1,q_2) = w_1q_1q_2 - l_s(1-q_1q_2) - C(q_1) - w_2q_2$ and $\pi_{S_2}(q_2|w_2) = w_2q_2 - l_s(1-q_2) - C(q_2)$.

I.1.2. A Parallel Supply Chain. When the suppliers incur a loss l_s under defect, the buyer's contracting problem in a parallel supply chain without traceability is formulated as

$$\begin{aligned}
\max_{\mathbf{w}} \quad & \pi_B(\mathbf{w}|\tilde{\mathbf{q}}(\mathbf{w})) = p\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) - l\left[1-\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w})\right] - \left(\sum_{i=1}^{2}w_i\right)\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) \\
\text{s.t.} \quad & \begin{cases} \pi_{S_i}(\tilde{q}_i(\mathbf{w})|w_i,\tilde{q}_{-i}(\mathbf{w})) \geqslant 0, i\in\{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(\mathbf{w}) = \arg\max\limits_{q_i} \; \pi_{S_i}(q_i|w_i,q_{-i}), i\in\{1,2\} & (\text{IC}_i) \end{cases}
\end{aligned} \tag{I.3}$$

where $\pi_{S_i}(q_i|w_i,q_{-i}) = w_iq_iq_{-i} - l_s(1-q_iq_{-i}) - C(q_i)$ for $i\in\{1,2\}$.

The buyer's contracting problem in a parallel supply chain with traceability is formulated as

$$\begin{aligned}
\max_{\mathbf{w}} \quad & \pi_B(\mathbf{w}|\tilde{q}_1(w_1),\tilde{q}_2(w_2)) = p\prod_{i=1}^{2}\tilde{q}_i(w_i) - l\prod_{i=1}^{2}\left[1-\tilde{q}_i(w_i)\right] \\
& + \frac{1}{2}(p-l)\sum_{i=1}^{2}\tilde{q}_i(w_i)\left[1-\tilde{q}_{-i}(w_{-i})\right] - \sum_{i=1}^{2}w_i\tilde{q}_i(w_i) \\
\text{s.t.} \quad & \begin{cases} \pi_{S_i}(\tilde{q}_i(w_i)|w_i) \geqslant 0, i\in\{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(w_i) = \arg\max\limits_{q_i} \; \pi_{S_i}(q_i|w_i), i\in\{1,2\} & (\text{IC}_i) \end{cases}
\end{aligned} \tag{I.4}$$

where $\pi_{S_i}(q_i|w_i) = w_iq_i - l_s(1-q_i) - C(q_i)$ for $i\in\{1,2\}$.

I.2. Equilibrium Analysis and Results

We show that the equilibrium outcomes remain qualitatively unchanged and our main insights regarding the impacts of traceability carry through. For example, in a serial supply chain, we find that the downstream supplier still invests disproportionately more than the upstream supplier compared to the case without traceability (see Propositions I.1 and I.2). More importantly, as shown in Figure I.2, all firms in a serial supply chain always benefit from traceability at the same time, and traceability always improves the upstream supplier's profit to a greater extent compared to the downstream supplier. On the other hand, in a parallel supply chain, as shown in Theorems

I.1 and I.2, while traceability always improves the buyer's profit and the total supply chain profit, it can reduce the suppliers' profits and the product quality particularly when the loss incurred by the buyer under defect is large.

Proposition I.1 (Equilibrium without Traceability in a Serial Supply Chain). *When the suppliers incur a loss* l_s *under defect, in a serial supply chain without traceability, there exists a unique equilibrium such that the buyer offers wholesale price* $w_1^{N\ddagger} = \frac{2\left[p+l-(\gamma-2)l_s\right]}{\gamma}$ *to the downstream supplier, the downstream supplier offers wholesale price* $w_2^{N\ddagger} = \frac{2(p+l)-(\gamma-2)(\gamma+2)l_s}{\gamma^2}$ *to the upstream supplier, and the downstream and the upstream suppliers' quality levels are* $q_1^{N\ddagger} = \left[\frac{2(p+l+2l_s)(\gamma-1)^{\frac{\gamma-1}{\gamma}}}{\theta\gamma^3}\right]^{\frac{1}{\gamma-2}}$ *and* $q_2^{N\ddagger} = \left[\frac{2(p+l+2l_s)(\gamma-1)^{\frac{1}{\gamma}}}{\theta\gamma^3}\right]^{\frac{1}{\gamma-2}}$, *respectively. Moreover,* $q_1^{N\ddagger}/q_2^{N\ddagger} = (\gamma-1)^{\frac{1}{\gamma}} \geqslant 1$.

Proposition I.2 (Equilibrium with Traceability in a Serial Supply Chain). *When the suppliers incur a loss* l_s *under defect, in a serial supply chain with traceability, there exists a unique equilibrium such that the buyer offers wholesale price* $w_1^{T\ddagger} = \left[\gamma w_2^{T\ddagger} + (\gamma-1)l_s\right]^{\frac{\gamma-1}{\gamma}} (w_2^{T\ddagger} + l_s)^{-\frac{1}{\gamma(\gamma-1)}} (\theta\gamma)^{\frac{1}{\gamma-1}} - l_s$ *to the downstream supplier, the downstream supplier offers wholesale price* $w_2^{T\ddagger}$ *to the upstream supplier, and the downstream and the upstream suppliers' quality levels are* $q_1^{T\ddagger} = \left[\gamma w_2^{T\ddagger} + (\gamma-1)l_s\right]^{\frac{1}{\gamma}} (w_2^{T\ddagger} + l_s)^{\frac{1}{\gamma(\gamma-1)}} \left(\frac{1}{\theta\gamma}\right)^{\frac{1}{\gamma-1}}$ *and* $q_2^{T\ddagger} = \left[\frac{w_2^{T\ddagger}+l_s}{\theta\gamma}\right]^{\frac{1}{\gamma-1}}$, *respectively, where* $w_2^{T\ddagger}$ *satisfies* $(p+l+l_s)\left(w_2^{T\dagger}+l_s\right)^{\frac{1}{\gamma(\gamma-1)}} \left(\frac{1}{\theta}\right)^{\frac{1}{\gamma-1}} \left(\frac{1}{\gamma}\right)^{\frac{\gamma}{\gamma-1}} \left[2\gamma^2 w_2^{T\dagger} + (\gamma-1)(2\gamma+1)l_s\right] = \left[\gamma^2 w_2^{T\dagger} + (\gamma-1)(\gamma+1)l_s\right]\left[\gamma w_2^{T\dagger} + (\gamma-1)l_s\right]^{\frac{\gamma-1}{\gamma}}$. *Moreover,* $q_1^{T\ddagger}/q_2^{T\ddagger} > (\gamma-1)^{\frac{1}{\gamma}} \geqslant 1$.

Proposition I.3 (Equilibrium without Traceability in a Parallel Supply Chain). *When the suppliers incur a loss* l_s *under defect, in a parallel supply chain without traceability, there exists a unique equilibrium such that the buyer offers wholesale price* $w_i^{N\dagger} = \frac{p+l-(\gamma-2)l_s}{\gamma}$ *to supplier* $i \in \{1,2\}$, *and supplier* i *chooses quality level* $q_i^{N\dagger} = \left(\frac{p+l+2l_s}{\theta\gamma^2}\right)^{\frac{1}{\gamma-2}}$.

Proposition I.4 (Equilibrium with Traceability in a Parallel Supply Chain). *When the suppliers incur a loss* l_s *under defect, in a parallel supply chain with traceability, there exists a unique equilibrium such that the buyer offers wholesale price* $w_i^{T\dagger} = \frac{p+l-2(\gamma-1)l_s}{2\gamma}$ *to supplier* $i \in \{1,2\}$, *and supplier* i *chooses quality level* $q_i^{T\dagger} = \left(\frac{p+l+2l_s}{2\theta\gamma^2}\right)^{\frac{1}{\gamma-1}}$.

Theorem I.1 (Comparison of Contracts in a Parallel Supply Chain). *When the suppliers incur a loss* l_s *under defect, in a parallel supply chain,*

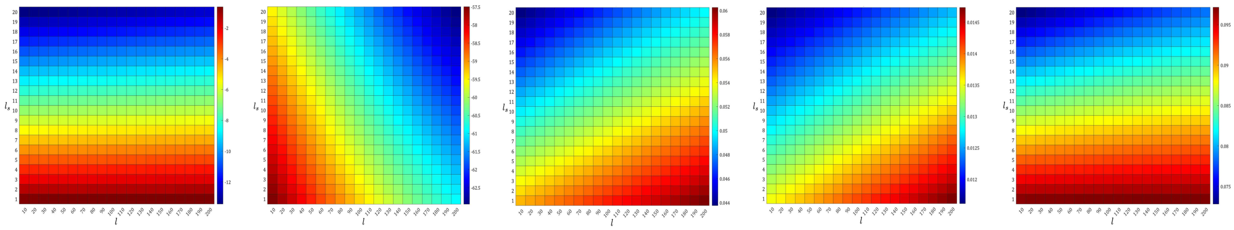
(a) traceability always decreases the wholesale prices;

(b) there exists a threshold for the loss under defect, $\tilde{l} \equiv \frac{\theta\gamma^2}{2^{\gamma-2}} - p - 2l_s$, *such that traceability improves the suppliers' quality levels if* $l \leqslant \tilde{l}$, *and reduces the suppliers' quality levels if* $l > \tilde{l}$.

Theorem I.2 (Comparison of Firm Profits in a Parallel Supply Chain). *When the suppliers incur a loss* l_s *under defect, in a parallel supply chain,* *(a) traceability always improves the buyer's expected profit and the total supply chain profit;*

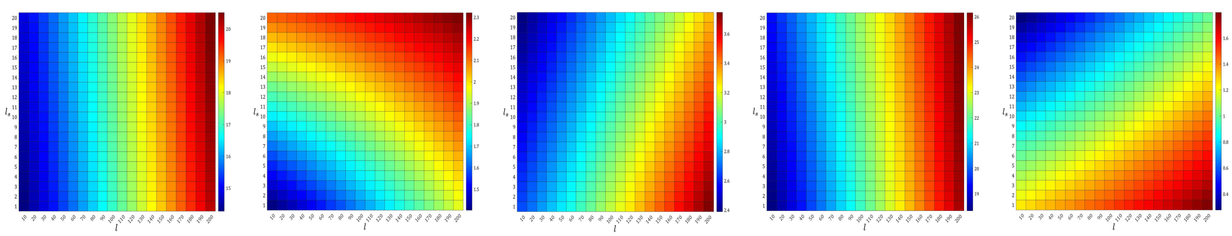
(b) traceability improves the suppliers' expected profits if $l \leqslant \tilde{l}$*, and reduces the suppliers' expected profits if* $l > \tilde{l}$*.*

Figure I.1 Comparison of Contracts in a Serial Supply Chain ($p = 1000$**,** $\theta = 300$**,** $\gamma = 5$**)**



(a) $w_1^{T\ddagger} - w_1^{N\ddagger}$ (b) $w_2^{T\ddagger} - w_2^{N\ddagger}$ (c) $q_1^{T\ddagger} - q_1^{N\ddagger}$ (d) $q_2^{T\ddagger} - q_2^{N\ddagger}$ (e) $q_1^{T\ddagger}/q_2^{T\ddagger} - q_1^{N\ddagger}/q_2^{N\ddagger}$

Figure I.2 Comparison of Firm Profits in a Serial Supply Chain ($p = 1000$**,** $\theta = 300$**,** $\gamma = 5$**)**



(a) $\pi_B^{T\ddagger} - \pi_B^{N\ddagger}$ (b) $\pi_{S_1}^{T\ddagger} - \pi_{S_1}^{N\ddagger}$ (c) $\pi_{S_2}^{T\ddagger} - \pi_{S_2}^{N\ddagger}$ (d) $\pi_{SC}^{T\ddagger} - \pi_{SC}^{N\ddagger}$ (e) $\left(\pi_{S_2}^{T\ddagger} - \pi_{S_2}^{N\ddagger}\right) - \left(\pi_{S_1}^{T\ddagger} - \pi_{S_1}^{N\ddagger}\right)$