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Managing Industry 4.0 supply chains with innovative and traditional products: Contract cessation points and value of information

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ABSTRACT

In supply chain management, how contract designs relate to the production system with traditional and Industry 4.0 innovative products (I4I products) is under-explored. In this paper, we fill this literature gap by studying a two-period model in which a manufacturer strategically chooses to incorporate an I4I product line into a traditional product line. In this context, we show that there exists a critical market potential threshold above which the sale of the I4I product is higher than that of the traditional product even when the former is sold at a higher price. For both wholesale price and linear two-part tariff contracts, we show that the contract cessation points and critical market potential threshold behave oppositely. We also find that the innovation level for the I4I product would be higher when the manufacturer's expected valuation towards the retailer's cost is higher than the actual one. We extend our base model to demonstrate that the innovation level of the I4I product is higher when the manufacturer uses a linear two-part tariff contract instead of a wholesale price contract. Finally, we uncover that the quantity-dependent innovation investment results in increased profitability and innovation level for the manufacturer provided that the innovation investment coefficient is sufficiently high.

1. Introduction

"Managing inventory operations with the help of technology and AI is key to building an efficient, sustainable, digitized and resilient supply chain".- Supply Chain Digital Magazine, 2022 (SCDM, 2022)

Globally, the supply chains are continuing to struggle against the repercussions of the ongoing conflict between Russia & Ukraine, the COVID-19 pandemic, and the ensuing economic crisis. Amidst these uncertainties companies are also being advised to take extra care in managing risks that could interrupt the supply chain by planning ahead as much as possible. With the ever-growing technology industry digitalizing the modern world, the Internet of Things (IoT) has an important part to play. Industry 4.0, relies upon IoT to achieve automatic and enhanced operations, aims at improving quality, reducing risk, and minimizing cost. Over the last few years, practitioners are adopting Industry 4.0 standards and technologies to achieve sustainable operations (Kamble et al., 2020). Under Industry 4.0, some of the sustainable practices adopted in the industry include reducing waste generation (Jabbour et al., 2021), improving resource efficiency (Qiu et al., 2015), and reducing logistic processes (Matana et al., 2020). Jabbour et al. (2018) believe that Industry 4.0 technologies aid in enhancing the environmental sustainability in manufacturing industries.

The sustainable impacts of digital supply chains embracing Industry 4.0 technologies have been realized in areas as diverse as textile and apparel supply chains (Kumar et al., 2022), automobile supply chains (Balakrishnan & Ramanathan, 2021), agricultural supply chains (Kamble et al., 2020), shipbuilding supply chains (Strandhagen et al., 2022), food supply chains (Kayikci et al., 2022), and others. In the automobile and ancillary industry, key global manufacturers to embrace Industry 4.0 technologies include Volkswagen, Bosch, Daimler, and BMW (Luthra et al., 2020). Similarly, in the textile industry, key players to invest in Industry 4.0 include Aditya Birla Fashion and Retail Limited (ABFRL), Gujarat Heavy Chemicals Limited (GHCL), and Arvind Limited (BusinessStandard, 2019). Other well-established companies which adopt and implement Industry 4.0 in their processes are Nestle, IBM, and Walmart (Choi et al., 2022; Tang & Veelenturf, 2019).

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The extant literature on Industry 4.0 technologies acknowledges the impact of Industry 4.0 technologies on the manufacturer–retailer interaction and supply chain management (Barbieri et al., 2021; Ghosh et al., 2020; Liu & Giovanni, 2019). Industry 4.0 technologies can impact the coordination mechanism and, thus, the degree of collaboration between the supply chain partners (Xu et al., 2020). Industry 4.0 technologies also possess the potential to alter the information visibility between supply chain partners and thus, can influence their decision-making. While the impact of Industry 4.0 technologies on supply chain coordination getting apparent, analytical studies investigating Industry 4.0 technologies in conjunction with coordination mechanisms are, however, few and limited (Barbieri et al., 2021; Hofmann et al., 2019). In this paper, we aim to bridge this gap by studying such a manufacturer–retailer relationship in the context of Industry 4.0 adoption. Next, we discuss the relevant background for our work.

1.1. Background

In the textile industry, which is considered to be one of the most polluting and highly resource-consuming industries, manufacturers are realizing the potential of sustainable Industry 4.0 solutions (ICN, 2021). India-based company GHCL, a traditional textile manufacturer of traditional products (defined as regular product(s) manufactured by the manufacturer before the incorporation of Industry 4.0 technology (Zhang et al., 2019)), has invested in the Applied DNAs "CertainT platform" to manufacture traceable and sustainable linen sheets using recycled Polyethylene Terephthalate (PET) biodegradable bottles (BusinessStandard, 2019). The bedding brand "REKOOP" of GHCL, an I4I product (defined as sustainable product(s) manufactured by the manufacturer using Industry 4.0 technologies (Liu & Giovanni, 2019), is manufactured by employing "CertainT platform" (GHCL, 2022). The traceability of "REKOOP" and recyclability of linen sheets have resulted in reduced landfill space, oil consumption, and atmospheric emission. The company is using the Systems, Applications, and Products (SAP) module in conjunction with fingerprinting technology to trace optical fiber inseminated into the fabric and hence, track product life-cycle until it is recycled (BusinessStandard, 2019). The company also has aggressive plans to build IoT-based plants in the future (ICN, 2021). Similarly, another leading textile manufacturer, ABFRL, has entered into a 10-year agreement with IBM for cloud services to scale their operations, improve productivity, and enhance customers' shopping experience (BusinessStandard, 2018). The technology application in ABFRL has replaced actual cloth samples with digital samples for wholesalers and hence, resulted in wastage reduction and reduction of product's go-to-market time. Similarly, Arvind Limited, a long-term franchise partner of a global apparel retailer GAP, is planning to invest in digital business transformation using Industry 4.0 technologies (BusinessStandard, 2019).

Bosch, a global manufacturer of auto ancillaries, has been manufacturing an anti-lock braking system (ABS), a traditional product, in its Chakan Plant in India. With the adoption of Industry 4.0 technology in its Chakan facility, each machine in the ABS production line has become interconnected with other machines and a part of Bosch's "International Production Network" for ABS. These production lines are, in turn, controlled by the Manufacturing Execution System (MES). The incorporation of these technologies has resulted in Bosch manufacturing ABS with zero quality defects (BusinessStandard, 2016). Bosch is investing in Industry 4.0 technologies to develop smart and sustainable solutions (BusinessStandard, 2022b) including an Artificial Intelligence (AI) and IoT-based analytic platform for energy and water management systems and a public infrastructure monitoring system (BusinessStandard, 2022a). In India, Bosch plans to implement Industry 4.0 in all of its manufacturing centers and is doing pilot testing of Industry 4.0 projects for energy management systems (BusinessStandard, 2016). The company believes that investment in Industry 4.0 shall lead to extra sales of components and would yield a return on investment in the next couple of years (BusinessStandard, 2016).

We observe from the aforementioned examples that traditional product manufacturers are investing in Industry 4.0 technology for producing I4I products and supplying both of them to their downstream partners. The downstream partner, after value-adding, sells the final product in the same end customer market. Thus, manufacturers incur an additional investment cost for I4I products. A study by Gartner reveals that chief information officers (CIOs) in Europe, the Middle East, and Africa (EMEA) expect their information technology budget to rise due to increased spending on enterprise digitalization which includes Industry 4.0 initiatives (Gartner, 2016). Another study suggests that top executives in Germany, Austria, and Switzerland (DACH region) are interested in pursuing Industry 4.0 initiatives in their enterprises. However, most of them report resource constraints as a major barrier in the pursuance of enterprise digital objectives (Gartner, 2019). In a supply chain, the manufacturer's information asymmetry of her downstream partner's cost is a common phenomenon that has been observed and examined in prior studies (Biswas et al., 2016; Teunter et al., 2018). Under such circumstances, the manufacturer assumes the downstream partner's cost to be a random variable with a lower limit and upper limit inferred from historical data. In this paper, we investigate this phenomenon using relevant mathematical models. We present our research questions below.

1.2. Research questions and contribution

In this paper, we are interested in investigating the impact of Industry 4.0-related costs and its impact on demand. We also investigate the impact of competition between Industry 4.0 and existing products in the same end market. In order to understand the phenomenon, as explained in the previous section, we formulate the following research questions.

- RQ 1: Under what conditions it wil be advantageous for a traditional product manufacturer to add an I4I production line to her manufacturing processes?
- RQ 2: What are the effects of information asymmetry on the manufacturer's innovation level, optimal contract design, the retailer's end-market pricing and product ordering strategies for I4I and traditional products?
- RQ 3: How do contract cessation points and quantity-dependent innovation investment impact the manufacturer's profitability and optimal contract design in the presence of both I4I and traditional product lines?

We use game theoretic modeling to address the aforementioned research questions. Using the backward induction (BI) method, we solve the Stackelberg game for two periods. In the first period, the manufacturer produces the traditional product only. In the second period, the manufacturer plans to incorporate an I4I product line in addition to the existing traditional product. We examine four scenarios for each of the two periods: wholesale price (W) and linear two-part tariff (L) contracts with consideration of the manufacturer's full and incomplete information about the retailer's cost for both the first and second periods. We carry out a numerical analysis to examine the manufacturer's and retailer's profits with the incorporation of the I4I product. We design a contract matrix to visualize the manufacturer's and retailer's contract preference with variations in consumer sensitivity to the I4I product, innovation investment parameter of Industry 4.0, and competition between I4I and traditional products. Finally, we incorporate the quantity-dependent innovation investment in our model and examine its impact on the manufacturer's profitability and innovation level of the I4I product.

Our paper demonstrates that there exists a market potential threshold for the I4I product, which, if exceeded, leads to increased sales of the I4I product compared to the traditional product. This result is important because the I4I product is priced higher in the market compared to the traditional product due to the innovation cost incurred by the manufacturer. We observe that with an increase in competition between I4I and traditional products and consumers' increased sensitivity to the I4I product, the market potential threshold of I4I products decreases. These results are hitherto unreported in the extant literature of Industry 4.0 product (Barbieri et al., 2021; Hofmann et al., 2019). We further observe that the manufacturer gains a monetary advantage and achieves a higher innovation level of the I4I product from the quantity-dependent innovation investment, provided that the quantity-dependent innovation investment is above a certain threshold. This result is of both theoretical and practical significance as innovation cost would be dependent on both the level of innovation and the quantity of such product produced. To the best of our knowledge they are not reported in the extant literature (Liu, Zhang, & Wu, 2023; Yang et al., 2022).

Through a two-period model, we analyze the manufacturer's strategic choice to incorporate the I4I product in terms of consumer sensitivity to the I4I product, innovation investment parameter of Industry 4.0, and competition between I4I and traditional products under full and incomplete information in the supply chain. Hitherto, this type of analysis has been unreported in the existing literature. Our paper analyses the effect of quantity-dependent innovation investment on the manufacturer's profitability and innovation level of the I4I product. This analysis of quantity-dependent innovation investment in the supply chain with simultaneous consideration of I4I and traditional products is under-explored. Thus, this study addresses the extant literature gap by examining contract cessation points for a supply chain with I4I and traditional products.

2. Related literature

In order to position our study in the context of the extant literature, we primarily focus on the stream of the supply chain (SC) literature that investigates Industry 4.0 and optimal contract design. Specifically, we discuss the extant literature of Industry 4.0 and relevant research gaps in this section. We end this section by discussing how our paper contributes to the existing literature.

Researchers have examined the effect of adopting Industry 4.0 technologies in SCs (Li & Li, 2022; Liu & Giovanni, 2019; Mithas et al., 2022; Olsen & Tomlin, 2020; Pandey et al., 2021; Sodhi et al., 2022). Cui et al. (2022) have examined the role of Industry 4.0 technologies for procurement in any SC. Balakrishnan and Ramanathan (2021) have focused on the application of Industry 4.0 technologies on SC resilience. Similarly, Cheng et al. (2021) have examined the connection between Industry 4.0 technologies and SC flexibility. Ivanov et al. (2019) and Pandey et al. (2021) have investigated the role of Industry 4.0 technologies in examining SC risks. Mastos et al. (2021) have examined the role of Industry 4.0 tools in circular SC management.

However, a closer examination of the extant literature reveals that few studies have focused on the importance of coordination, trade cut-off policies, and value-of-information in a relationship between a manufacturer and her downstream retailer in the context of Industry 4.0-based SC (Barbieri et al., 2021; Hofmann et al., 2019). In the extant literature on the coordination of Industry 4.0-based SCs, Giovanni (2019) has focused on the outcomes of smart contracts under static and dynamic SC frameworks, where an AI system supports decision-making and decides optimal contract terms. While Giovanni (2021) has analyzed coordination in Industry 4.0-based integrated SC with consideration of vendor-managed inventory, he has not considered the calculations of value-of-information and trade cut-off points. Ghosh et al. (2020) have analyzed the effects of strategic decisions and competition on coordination without considering the impact of either value-of-information and trade cut-off policies. Kumar et al. (2022) have examined the coordination mechanisms for the digital SC using the Industry 4.0-based virtual organization model; the authors do not investigate the influence of cut-off policies. In the current manuscript, we address these literature gaps by investigating the value-of-information and the impact of trade cut-off policies (or contract cession points) in the context of a dyadic supply chain relationship.

In the Industry-4.0-based SC literature, a limited number of scholarly works have focused on the context of value-of-information. Yang et al. (2022) have studied the value-of-information sharing in an SC for low-carbon products and found the benefits of blockchain implementation in SCs with limited information sharing. They calculate the value-of-information based on value-added service efficiency parameters. They do not investigate the impact of information asymmetry about the cost of production on the computation of value-of-information. Liu, Zhang, and Wu (2023) have investigated the value-of-information for sharing via blockchain in an SC with a retail platform and a manufacturer participating in direct and indirect selling. However, scholars have not considered the case of value-of-information based on information asymmetry about the marginal cost of production. None of the authors have investigated the impact of demand expansion coefficient, competition, and innovation level on value-of-information. In this paper, we further address this literature gap. Liu and Giovanni (2019) have investigated the coordination mechanisms with consideration of Industry 4.0-based innovation investments in the SC. De Giovanni (2020) have considered an SC managed through either a traditional online system or an Industry 4.0-based product (blockchain) with the SC firms considering the costs of both. They examined the suitability of smart contracts as coordinating mechanisms in these supply chains. Biswas et al. (2023) have investigated the choice of Industry 4.0 adoption (blockchain technology) for a manufacturer–retailer SC where firms weighed product traceability against negative environmental impacts. However, none of these aforementioned studies have investigated the impact of simultaneously managing traditional and Industry-4.0 products on SC coordination and calculation of trade cut-off policies and value-of-information. In our paper, we address this literature gap by examining the coordination mechanisms, pricing, and ordering strategy for an SC wherein both I4I and traditional products are simultaneously considered; we further examine the contract cessation points, model information asymmetry, and determine the value of information in this SC with dual product strategy. We present the summary of the literature review in Table A.1 of online supplementary material.

3. Model formulation

In order to understand how a manufacturer strategically decides the incorporation of an I4I product channel in her business, we develop a two-period dyadic SC model consisting of one upstream manufacturer (index: M) and one downstream retailer (index: R) following the real-life instances described in Section 1.1. In the first period, $P = 1$, M produces a traditional product (index: B) at a per unit cost of $y(> 0)$ and sells it through R at a price p_{1B}. The demand of this product in $P = 1$ is given by the following function: $d_{1B} = \beta - p_{1B}$, where $\beta(> 0)$ designates the market potential of the traditional product in period $P = 1$. R's per unit cost is $z(> 0)$, and M sells her product to R using either a wholesale price (index: W) contract or a linear two-part tariff (index: L) contract. Subsequently, in the second period, $P = 2$, M decides whether to continue just producing the traditional product (like period $P = 1$) or to introduce the I4I production (index: I) process along with the existing traditional product line by incurring an additional cost for technology adoption. As described in Section 1.1, when M plans to introduce an I4I production line in period $P = 2$, she incurs this additional cost due to various factors such as increasing industry pressure for adopting supply chain Industry 4.0 standards, adaptation to changing consumer preferences, change in governmental policies, or a combination of these factors.

The overall market potential of products in period $P = 2$ is considered to be $\beta(> 0)$. If the manufacturer decides to incorporate an I4I product line into the second period, then the fraction of market potential attributed to the I4I product is $\phi_I \in [0,1]$ and the fraction of market potential attributed to a traditional product is $\phi_{2B} \in [0,1]$. Alternatively, we can say that (i) ϕ_I represents the fraction of the overall market potential for the period $P = 2$ that gets cannibalized due to the introduction of the I4I product line and (ii) ϕ_{2B} represents the fraction of the overall market potential for the period $P = 2$ that is retained by the traditional product. Therefore, we have: $\phi_I + \phi_{2B} = 1$.

The demand for the I4I product in period $P = 2$ is adopted from the literature as follows. As evident from our discussion in Section 1.1 and extant literature in Section 2, we understand that supply chains are adopting Industry 4.0 technology in their production process through innovation (Liu & Giovanni, 2019; Liu, Zhao, Chen & Wang, 2023). We capture this product innovation through the coefficient η. Liu and Giovanni (2019) further argue that customers are sensitive to I4I products. We capture this consumer sensitivity through a demand expansion coefficient for Industry 4.0 products (denoted by λ). Thus, the effective increased demand that stems from I4I products is given by: $\lambda\eta$ where $\lambda > 0$ and $\eta > 0$. This modeling technique is in line with the generalized supply chain modeling of any quality parameter (Banker et al., 1998; Ghosh & Shah, 2015). Thus, the overall demand in $P = 2$ is given by: $d_I = \beta\phi_I - p_I + \delta p_{2B} + \lambda\eta$, where $p_I(> 0)$ is the per unit price of the I4I product, $p_{2B}(> 0)$ is the per unit price of the traditional product and $\delta(> 0)$ is the cross-price sensitivity. The demand for traditional products in $P = 2$ is given by: $d_{2B} = \beta\phi_{2B} - p_{2B} + \delta p_I$. Through these demand functions, we model horizontal competition between I4I and traditional products of the same manufacturer as a manufacturing firm typically does not abandon its established product line due to the launch of new technology in the market. The competition parameter δ captures the switching of customer's choice and the resultant product demand loss due to substitutable products in the market (Biswas et al., 2016). This assumption allows us to model the situation faced by many Industry 4.0 companies as discussed in Section 1.1. M's per unit cost of production in period $P = 2$ is $y(> 0)$, and her cost of innovation is $\mu\eta^2$, where μ is the manufacturer's innovation cost parameter. The convex increasing innovation cost allows us to model the innovation effort of a manufacturing firm in a way that it is not beneficial for the manufacturer to do innovation beyond a certain level (Ghosh & Shah, 2012; Raj et al., 2018). The retailer's per unit cost in period $P = 2$ is $z(> 0)$. For the purpose of expositional simplicity, we further assume that the discount rate for period $P = 2$ is zero.[1] We describe our supply chain timeline in Fig. 1.

In this particular setup, we analyze the optimization problems of M for periods $P = 1$ and $P = 2$ in both full and asymmetric information setups. In the full information (index: F) set up, M and R are aware of each other's cost, transfer prices, and demand structures. In the asymmetric information (index: A) set up, we assume that M does not know R's per unit cost but holds the following belief about this cost parameter: z is a random variable in the following range: $[\underline{z}, \overline{z}]$, where $[0 \le \underline{z} \le \overline{z} \le \infty]$; (ii) based on historical data, M knows the probability distribution $G(z)$ of z (Liu & Çetinkaya, 2009). Therefore, in the full information setup, M knows the exact value of z, and in the asymmetric information setup, M knows the probability distribution $G(z)$. The meaning of notations used in the paper is presented in Table 1.

In order to understand M's strategic decision of incorporating innovation production in period $P = 2$, we further incorporate the reservation profits of M and R into our model in the following way. From the model formulation, we observe that the profits of M and R decrease in R's per unit cost z. Therefore, M and R can design their cost-based contract cessation policies such that they refuse to trade with each other if they do not earn their respective reservation profits: $\overline{\pi}_{2M}$ and $\overline{\pi}_{2Ri}$, where $i \epsilon [I, 2B]$ respectively. With the expected profit level descending below the reservation level, the supply chain agent (M or R) loses the trade incentive. The four scenarios of manufacturer–retailer interaction emerge depending on the type of contract (W or L) and the availability of information (full or asymmetric), and we present them in Table B.1 of online supplementary material.

M offers her contract term(s) such that R's incentive compatibility constraint (IC_{2R}) is satisfied. This constraint signifies that the retailer's order quantity decision is based on her own profit-maximizing criteria (Corbett & Tang, 1999). The individual rationality constraints of M and R are given by IR_{2M} and $IR_{2Ri}, i\epsilon[I, 2B]$ respectively; individual rationality constraints ensure that either M or R participates in the trade if and only if their earn their reservation profit. We present the manufacturer's W contract problem for both F and A in Section 4. Subsequently, we extend our model using channel coordinating L contract and present it in Section 6; we also analyze the impact of quantity-dependent innovation cost.

We use the BI method to solve the manufacturer's optimization problems and present the relevant derivations of theorems in Appendix. In order to compare these results with that of a benchmark case, we examine the centralized SC in the next section. The optimal parameters of the centralized SC are used for benchmarking in our subsequent analysis.

3.1. Centralized supply chain (c) — benchmark solution

In a centralized structure, the manufacturer and the retailer are vertically integrated, and a central planner (CP) makes the optimal SC decisions. The central planner's optimization problems are described below. CP's Problem in Period 1:

$$d_{1B}^* = \max_{d_{1B}} \pi_{1C}(d_{1B}) = (p_{1B} - (y + z))d_{1B}, \quad \text{where} \quad d_{1B} = \beta - p_{1B} \tag{1}$$

CP's Problem in Period 2:

$$(d_{2B}^*, d_I^*) = \max_{d_{2B}, d_I} \pi_{2C}(d_{2B}, d_I) = (p_{2B} - (y + z))d_{2B} + \{(p_I - (y + z))d_I - \mu\eta^2\},$$

$$\text{where} \quad d_I = \beta\phi_I - p_I + \delta p_{2B} + \lambda\eta \quad \text{and} \quad d_{2B} = \beta\phi_{2B} - p_{2B} + \delta p_I \tag{2}$$

The central planner's objective function in $P = 1$ is concave in d_{1B} for positive values of d_{1B} and her objective function in $P = 2$ is concave in (d_{2B}, d_I, η) iff the following conditions hold: $\delta < 1$ and $\mu > \frac{\lambda^2}{4(1-\delta^2)}$. We derive these conditions from the Hessian matrix of the central planner's optimization problem of $P = 2$. Under these conditions of concavity, we derive the central planner's optimal decisions for both periods, and they are presented in the theorem below.

Theorem 1. *In a centralized supply chain, the following statements hold: (i) in period $P = 1$, the central planner's optimal production quantity is: $[d_{1B}^*]_C = \frac{\beta-(y+z)}{2}$ and her optimal retail price is: $[p_{1B}^*]_C = \frac{\beta+(y+z)}{2}$, (ii) in period $P = 2$, if the following condition holds: $\frac{\mu(V_I+\delta V_{2B})^2}{J} + \frac{V_{2B}^2}{4} < \frac{(\beta-(y+z))^2}{4}$, then it is not advantageous for the central planner to produce I4I product. In this case, she continues with the production of traditional products and her optimal decisions are equal to those of period $P = 1$, and (iii) in period $P = 2$, if the following condition holds: $\frac{\mu(V_I+\delta V_{2B})^2}{J} + \frac{V_{2B}^2}{4} > \frac{(\beta-(y+z))^2}{4}$, then it is advantageous for the central planner to produce I4I product in addition to the existing traditional channel. In this case, the central planner's optimal traditional production quantity is: $[d_{2B}^*]_C = \frac{V_{2B}}{2}$, the optimal I4I production quantity is: $[d_I^*]_C = \frac{V_I}{2} + \frac{(\lambda^2/2)(V_I+\delta V_{2B})}{J}$, and the optimal innovation level is: $[\eta^*]_C = \frac{\lambda}{J}(V_I + \delta V_{2B})$, where $V_i = [\beta\phi_i - (y + z)(1 - \delta)]$, $i = \{I, 2B\}$, and $J = 4\mu(1 - \delta^2) - \lambda^2$.*

[1] An exogenous non-zero discount rate ($r(> 0)$) would change the net present values of M and R from $(\pi_{1i}(\cdot) + \pi_{2i}(\cdot))$ to $(\pi_{1i}(\cdot) + \pi_{2i}(\cdot)/(1 + r))$ where $i \in \{M, R\}$; this is not going to have any significant impact on our main findings.

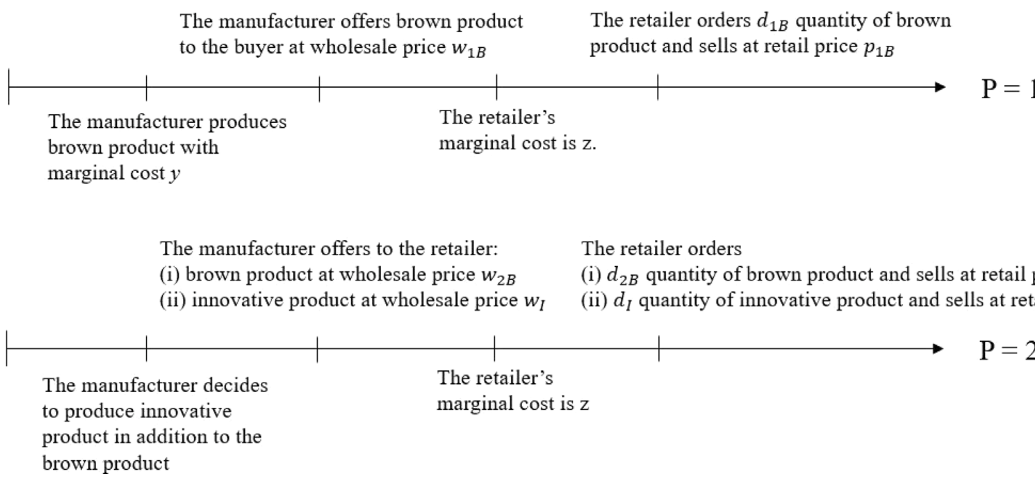


Fig. 1. Timeline diagram.

Table 1
Notations.

Notations	Meaning	Notations	Meaning
λ	Demand expansion coefficient of Industry 4.0	C	Centralize supply chain
d	Demand quantity	L	Linear two-part tariff contract
w	Unit wholesale price	A	Incomplete information
μ	Innovation cost parameter of Industry 4.0	F	Full information
δ	Cross price sensitivity (competition coefficient)	β	Total market potential
η	Product innovation level due to Industry 4.0	T	Franchise fee
H	Coefficient of quantity dependent innovation investment	π	Total profit
ϕ_I	Market potential of I4I product in Period $P = 2$	$\overline{\pi}$	Reservation profit
ϕ_{2B}	Market potential of traditional product in Period $P = 2$	B	Traditional product
$G(z)$	Probability distribution of retailer's unit cost	I	I4I product
$g(z)$	Continuous density function of retailer's unit cost	z	Retailer's unit cost
W	Wholesale price contract	$\underline{z}$	Lower limit of retailer's unit cost
WQ	Wholesale price contract with quantity dependent investment	M	Manufacturer
$1M1B$	Manufacturer with traditional product in period $P = 1$	p	Unit retail price
$1R1B$	Retailer with traditional product in period $P = 1$	$\hat{z}$	Cutoff point in retailer's unit cost
$2MI$	Manufacturer with I4I product in period $P = 2$	y	Manufacturer's unit cost
$2M2B$	Manufacturer with traditional product in period $P = 2$	ρ_z	Expected value of retailer's unit cost
$2RI$	Retailer with I4I product in period $P = 2$	R	Retailer
$2R2B$	Retailer with traditional product in period $P = 2$	$\overline{z}$	Upper limit of retailer's unit cost

Theorem 1 provides us with a couple of important insights about a central planner's choice of adding an I4I production line in period $P = 2$. The central planner begins in period $P = 1$ with exclusive traditional product manufacturing and subsequently decides about I4I production in $P = 2$ iff her total profit level increases by incorporation of such a product line.

Theorem 1 further provides us with the condition under which a central planner's profit in $P = 2$ is improved by incorporating an I4I product line compared to the situation where the central planner continues with only the traditional product line in $P = 2$. Therefore, the introduction of I4I production process is subject to a conducive condition as discussed in Theorem 1(iii). We also observe anecdotal support for such a condition when Arvind Limited has adopted innovative technology to cut down water wastage by 8 million liters per day, anticipating an increase in profitability (Section 1.1). Bosch has also reported an increase in its profitability to €5.3bn in 2017 (€1.0bn increase from 2016) by incorporating Industry 4.0 technology in their production process (FT, 2018).

From Theorem 1, we can derive the central planner's pricing strategies for I4I and traditional products as follows. The central planner's optimal price for traditional product in $P = 2$ is: $[p^*_{2B}]_C = (y + z) + \frac{2\mu(V_{2B}+\delta V_I)}{J} - \frac{(\lambda^2/2)V_{2B}}{J}$ and optimal price for I4I product is: $[p^*_I]_C = (y + z) + \frac{2\mu(V_I+\delta V_{2B})}{J}$. From these expressions, we observe that the difference in retail prices of traditional and I4I products is: $[p^*_I]_C - [p^*_{2B}]_C = \frac{2\mu}{J}(1 - \delta)(V_I - V_{2B}) + \frac{\lambda^2}{2J}V_{2B}$. From this expression, we observe that the I4I product's price is more than the traditional product's price if $V_I > V_{2B}$. Therefore, the introduction of a higher-priced I4I product in $P = 2$ allows the central planner to push more traditional products into the market. We have also conducted a robustness check for our model using non-linear demand functions, which is reported in the Appendix E of Online Supplementary Material.

Under equilibrium conditions, we demonstrate that the market potential of the I4I product has to be greater than a certain threshold level so that the central planner's overall profit increases by introducing this product in period $P = 2$. Based on these thresholds, the central planner can design her optimal product introduction strategy and we present it below through Proposition 1.

Proposition 1. *In period $P = 2$, the central planner's optimal product introduction strategy is as follows: (i) when $\phi_I < [\bar{\phi}_I]_C$, the central planner should not introduce I4I product in the market as her profit decreases in market potential ϕ_I, (ii) when $[\bar{\phi}_I]_C < \phi_I < [\bar{\bar{\phi}}_I]_C$, the central planner should introduce I4I product in the market though her profit would be less compared to the case where I4I product is not introduced, and (iii)* *when $\phi_I > [\bar{\bar{\phi}}_I]_C$, the central planner should introduce I4I product in the market as her overall profit would be more than the case where I4I product is not introduced, where* $[\bar{\phi}_I]_C = \frac{4\mu(1-\delta)-(\lambda^2/\beta)[\beta-(y+z)(1-\delta)]}{8\mu(1-\delta)-\lambda^2}$ *and* $[\bar{\bar{\phi}}_I]_C = \frac{1}{\beta(1-\delta)}\left[\sqrt{\frac{4\mu(1-\delta^2)-\lambda^2}{4\mu}}[\beta-(y+z)] - [\beta\delta-(y+z)(1-\delta^2)]\right]$.

Proposition 1 provides us with an interesting insight into the central planner's I4I product introduction strategy. When the market potential of the I4I product is very small: $\phi_I < [\bar{\phi}_I]_C$, it is not beneficial for the central planner to introduce the I4I product at all. When the market potential of the I4I product is moderate: $[\bar{\phi}_I]_C < \phi_I < [\bar{\bar{\phi}}_I]_C$, the central planner should introduce the I4I product in the market to gain first mover advantage as her overall profit, though less than the situation where she does not introduce the I4I product, shows an increasing trend in ϕ_I. When the market potential of the I4I product is high: $\phi_I > [\bar{\bar{\phi}}_I]_C$, the central planner earns more than the situation where she does not introduce the I4I product in period $P = 2$ and thus it is profitable for the central planner to introduce the I4I product.

Proposition 1 establishes that when the I4I product's market potential exceeds the following threshold: $\phi_I > [\bar{\phi}_I]_C$, the I4I product's optimal retail price and quantity become greater than those of the traditional product. The aforementioned condition is of particular importance to understand the decision of a central planner in $P = 2$. Even when both products have the same market potential in period $P = 2$: $\phi_I = \phi_{2B}$, the I4I product commands a higher price in the market: $[p_I^*]_C > [p_{2B}^*]_C$ and in spite of this higher price, the I4I product's demand is higher than traditional product's demand: $[d_I^*]_C > [d_{2B}^*]_C$. Under the condition of equal market potential for both products, the demand for I4I products increases due to higher consumer sensitivity (λ) towards I4I products; as a result, a central planner is able to sell more I4I products in the market while charging higher retail prices for the same.

We present a numerical example to support the discussion of the aforementioned proposition in Appendix C of the online supplementary material. From the numerical example, we observe that at both small and moderate values of the I4I product's market potential, the central planner's profit from introducing the I4I product in $P = 2$ is less than the central planner's profit without introducing the I4I product. At a higher I4I product's market potential, the central planner's profit from introducing the I4I product in $P = 2$ is more than the case where the central planner does not introduce the I4I product.

4. Manufacturer's problem in a decentralized setup

In this section, we present the manufacturer M's problem in a decentralized dyadic supply chain setup for both full and asymmetric information scenarios. Since we are interested in analyzing M's strategic choice of I4I channel incorporation in period $P = 2$, we present M's optimization problem using the W contract in both periods. We investigate the effect of channel coordinating contracts on the overall SC performance in Section 6.

While using the W contract (or L contract, as shown in Section 6) in both periods, M's optimal decisions are as follows. In period $P = 1$, M chooses her wholesale price w_{1B}^* (or w_{1B}^* and T_{1B}^*) to optimize her profit from selling the traditional product. In period $P = 2$, M chooses her wholesale prices w_{2B}^* (or w_{2B}^* and T_{2B}^*) and w_I^* (or w_I^* and T_I^*) to optimize her overall profit from selling I4I and traditional products. In period $P = 2$, M may also choose to introduce the I4I product channel if and only if such a decision enables her to earn a higher profit than her continuation with the traditional product. M's generalized optimization problems in periods $P = 1$ and $P = 2$ are presented below.

Manufacturer's Generalized Optimization Problem in Period 1:

$$(w_{1B}^*, T_{1B}^*) = \max_{w_{1B},T_{1B}} E[\pi_{1M}(w_{1B})] = \int_{\underline{z}}^{\bar{z}} (w_{1B} - y) d_{1B}(z) dz + T_{1B} \tag{3}$$

$$IC_{1R} : d_{1B}^*(z) = \max_{d_{1B}} \pi_{1R}(d_{1B}) = (p_{1B} - w_{1B} - z) d_{1B}(z) - T_{1B} \geq \bar{\pi}_{1R1B}$$
$$\text{where } d_{1B} = \beta - p_{1B} \tag{4}$$

Manufacturer's Generalized Optimization Problem in Period 2:

$$(w_{2B}^*, w_I^*, T_{2B}^*, T_I^*, \eta^*) = \max_{w_{2B},w_I,T_{2B},T_I,\eta} E[\pi_{2M}(w_{2B}, w_I, T_{2B}, T_I, \eta)]$$
$$= \int_{\underline{z}}^{\bar{z}} (w_{2B} - y) d_{2B}(z) dz + T_{2B} + \int_{\underline{z}}^{\bar{z}} (w_I - y) d_I(z) dz + T_I - \mu\eta^2 \tag{5}$$

$$IC_{2R} : (d_{2B}^*(z), d_I^*(z)) = \max_{d_{2B},d_I} \pi_{2R}(d_{2B}, d_I) = \max_{d_{2B},d_I} \{\pi_{2R2B}(d_{2B}(z)) + \pi_{2RI}(d_I(z))\} \tag{6}$$

where, $\pi_{2R2B}(d_{2B}) = (p_{2B} - w_{2B} - z) d_{2B} - T_{2B} \geq \bar{\pi}_{2R2B}$,
$\pi_{2RI}(d_I) = (p_I - w_I - z) d_I - T_I \geq \bar{\pi}_{2RI}$,

$$d_{2B} = \beta\phi_{2B} - p_{2B} + \delta p_I, \text{ and } d_I = \beta\phi_I - p_I + \delta p_{2B} + \lambda\eta \tag{7}$$

M calculates her contract parameters in both periods such that R's incentive compatibility constraints are satisfied. IC_{1R} and IC_{2R} represent R's incentive compatibility constraints in period $P = 1$ and $P = 2$ respectively. We present the solution to these optimization problems below.

4.1. Analysis of full information game

In this section, we present M's wholesale prices in a full information game setting. In the full information game, M knows the exact value of R's unit cost and is able to optimize her exact objective functions. These results are presented in the theorem below.

Theorem 2.

a. *When the manufacturer M uses W contracts in both periods, her optimal decisions are characterized as follows: (i) in period $P = 1$, M's optimal wholesale price is: $[w_{1B}^*]_{FW} = \frac{\beta+(y-z)}{2}$, and (ii) in period $P = 2$, either of the following two happens:*
   (1) If $\frac{\mu(V_I+\delta V_{2B})^2}{J_\omega} + \frac{V_{2B}^2}{8} < \frac{(\beta-(y+z))^2}{8}$, then it is not profitable for M to add an I4I channel, she continues with the production of traditional products, and her optimal decision is equal to that of period $P = 1$.
   (2) Otherwise, it is profitable for M to produce I4I product in addition to the traditional product; in this case, M's optimal traditional product wholesale price is: $[w_{2B}^*]_{FW} = y + \frac{4\mu(V_{2B}+\delta V_I)}{J_\omega} - \frac{(\lambda^2/2)V_{2B}}{J_\omega}$, optimal I4I product wholesale price is: $[w_I^*]_{FW} = y + \frac{4\mu(V_I+\delta V_{2B})}{J_\omega}$, and optimal innovation level is: $[\eta^*]_{FW} = \frac{\lambda}{J_\omega}(V_I + \delta V_{2B})$.
b. *The retailer R's optimal decisions are characterized as follows: (i) in period $P = 1$, her optimal order quantity is: $[d_{1B}^*]_{FW} = \frac{\beta-(y+z)}{4}$, (ii) in period $P = 2$, either of the following two happens:*
   (1) If M does not add a I4I channel, then R's optimal decision is equal to that of $P = 1$.
   (2) If M adds an I4I channel, then R's optimal traditional product order quantity is: $[d_{2B}^*]_{FW} = \frac{V_{2B}}{4}$, and optimal I4I product order quantity is: $[d_I^*]_{FW} = \frac{V_I}{4} + \frac{(\lambda^2/4)(V_I+\delta V_{2B})}{J_\omega}$, where $V_i = [\beta\phi_i - (y + z)(1 - \delta)]$, $i=\{I, 2B\}$, and $J_\omega = 8\mu(1 - \delta^2) - \lambda^2$.

In Theorem 2 we establish the condition under which M should introduce an I4I product in $P = 2$ to increase profitability. In $P = 2$, if the following condition: $\frac{\mu(V_I+\delta V_{2B})^2}{J_\omega} + \frac{V_{2B}^2}{8} > \frac{(\beta-(y+z))^2}{8}$ holds as implied in Theorem 2a, then M's profit increases by introducing an I4I product line along with the traditional product line. By comparing with Theorem 1(iii), we understand that the condition for introducing an I4I product is more relaxed in a decentralized setup when M introduces it through R using W contract. We further support our finding with the following anecdotal evidences: ABFRL is investing in Industry 4.0 technology to reduce its go-to-market time (Section 1.1). ABFRL is adopting I4I production process as it anticipates that its market condition has become conducive to earning higher profit through I4I production. Similarly, GHCL has reduced its crude oil consumption and thus increased its profitability by producing recyclable linen sheets manufactured using Industry 4.0 technology (Section 1.1). Next, we present the optimal product introduction strategy for M in Proposition 2.

Proposition 2. *Manufacturer M's I4I product introduction strategy is as follows: (i) If $\phi_I < [\bar{\phi}_I]_{FW}$, then M should not introduce I4I product as her profit decreases in ϕ_I; (ii) If $[\bar{\phi}_I]_{FW} < \phi_I < [\bar{\bar{\phi}}_I]_{FW}$, then M should introduce I4I product in the market even though her profit would be less compared to the situation where the I4I product is not introduced; (iii) If $\phi_I > [\bar{\bar{\phi}}_I]_{FW}$, then M should introduce I4I product in the market as introduction of I4I product ensures higher profitability, where $[\bar{\phi}_I]_{FW} = \frac{8\mu(1-\delta)-(\lambda^2/\beta)[\beta-(y+z)(1-\delta)]}{16\mu(1-\delta)-\lambda^2}$ and $[\bar{\bar{\phi}}_I]_{FW} = \frac{1}{\beta(1-\delta)}\left[\sqrt{\frac{8\mu(1-\delta^2)-\lambda^2}{8\mu}}[\beta-(y+z)] - [\beta\delta-(y+z)(1-\delta^2)]\right]$.*

From Proposition 2, we observe that when the market potential of the I4I product is very small: $\phi_I < [\bar{\phi}_I]_{FW}$, M would not be benefited by introducing the I4I product. When the market potential of the I4I product is moderate: $[\bar{\phi}_I]_{FW} < \phi_I < [\bar{\bar{\phi}}_I]_{FW}$, M's overall profit increases with increase in the market potential of I4I product: ϕ_I. M should introduce the I4I product to gain a first-mover advantage. However, her overall profit still remains less than what she would have achieved by not introducing the I4I product. When the market potential of the I4I product is high: $\phi_I > [\bar{\bar{\phi}}_I]_{FW}$, then it is profitable for M to introduce the I4I product as her overall profit is more than the situation where she does not introduce the I4I product in period $P = 2$. By comparing Proposition 2 with Proposition 1, we understand that: (i) $[\bar{\phi}_I]_{FW} > [\bar{\phi}_I]_C$ and (ii) $[\bar{\bar{\phi}}_I]_{FW} > [\bar{\phi}_I]_C$. This comparison helps us to understand that in a decentralized setup, M requires a higher market potential than a centralized setup for (i) launching an I4I product and (ii) making such a product line profitable.

We present a numerical example to support the discussion of the aforementioned proposition in Appendix C of the online supplementary material. From the numerical example, we observe that the threshold value of the market potential: $[\bar{\phi}_I]_{FW}$ in FW contract is larger than the corresponding threshold value calculated for the centralized supply chain: $[\bar{\phi}_I]_C$. This is attributed to the SC's double marginalization problem due to the usage of the FW contract. As a result, in this case, the manufacturer's decision to adopt Industry 4.0 to increase its profitability gets affected by both the competition between traditional and I4I products and consumer sensitivity to the I4I product. From numerical analysis, we observe that the threshold is decreasing in both consumer sensitivity to the I4I product and competition between I4I and traditional products, and is increasing in the innovation investment parameter of Industry 4.0.

The introduction of the I4I channel in period $P = 2$ changes R's pricing strategies and market shares in the following way.

Proposition 3. *If M introduces I4I product in $P = 2$, then R's optimal I4I product retail price is: $[p_I^*]_{FW} = (y+z)+\frac{3}{2}\left[\frac{4\mu(V_I+\delta V_{2B})}{J_\omega}\right]$, optimal traditional product retail price is: $[p_{2B}^*]_{FW} = (y+z)+\frac{3}{2}\left[\frac{4\mu(V_{2B}+\delta V_I)}{J_\omega} - \frac{(\lambda^2/2)V_{2B}}{J_\omega}\right]$, market share of I4I product is: $\frac{\left[\frac{V_I}{V_{2B}}\left(1+\frac{\lambda^2}{J_\omega}\right)+\frac{\delta\lambda^2}{J_\omega}\right]}{1+\left[\frac{V_I}{V_{2B}}\left(1+\frac{\lambda^2}{J_\omega}\right)+\frac{\delta\lambda^2}{J_\omega}\right]}$, and market share of traditional product is: $\frac{1}{1+\left[\frac{V_I}{V_{2B}}\left(1+\frac{\lambda^2}{J_\omega}\right)+\frac{\delta\lambda^2}{J_\omega}\right]}$, where $V_i = [\beta\phi_i-(y+z)(1-\delta)]$, $i=\{I,2B\}$, and $J_\omega = 8\mu(1-\delta^2)-\lambda^2$.*

From Proposition 3, we calculate the difference in retail prices of I4I and traditional products: $[p_I^*]_{FW} - [p_{2B}^*]_{FW} = \frac{3}{2}\left[\frac{4\mu}{J_\omega}(1-\delta)(V_I-V_{2B})+\frac{\lambda^2}{2J_\omega}V_{2B}\right]$. Similarly, the difference in wholesale prices of I4I and traditional products is: $[w_I^*]_{FW} - [w_{2B}^*]_{FW} = \frac{4\mu}{J_\omega}(1-\delta)(V_I-V_{2B})+\frac{\lambda^2}{2J_\omega}V_{2B}$. From these expressions, we realize that the I4I product's retail and wholesale prices, both would be higher than that of the traditional product's retail and wholesale prices respectively, provided the following condition is satisfied: $V_I > V_{2B}$. As M charges an extra amount for her innovation efforts, both M's wholesale price and R's retail price are increased.

Even when both products have the same market potential: $\phi_I = \phi_{2B}$, the I4I product would be priced higher in the market: $[p_I^*]_{FW} > [p_{2B}^*]_{FW}$ and the I4I product's demand would be higher than traditional product's demand: $[d_I^*]_{FW} > [d_{2B}^*]_{FW}$. When customer sensitivity toward I4I products (λ) is high, the demand for I4I products increases, and M is able to sell more I4I products through R while charging higher retail prices in the market.

4.2. Analysis of asymmetric information game

In this section, we present the manufacturer M's wholesale prices under the asymmetric information game setting. In an asymmetric information game, M does not know R's per unit cost z but knows $z \in [\underline{z}, \overline{z}]$ with cumulative probability distribution $G(z)$. M's optimization problem under asymmetric information is presented and solved in Appendix.

Theorem 3. *In an asymmetric information setting,*

a. *If the manufacturer M uses W contracts in both periods, her optimal decisions are characterized as follows: (i) in period $P = 1$, M's optimal wholesale price is: $[w_{1B}^*]_{AW} = \frac{\beta+(y-\rho_z)}{2}$, (ii) in period $P = 2$, either of the following two happens:*
   (1) If $\frac{\mu\{V_I(\rho_z)+\delta V_{2B}(\rho_z)\}^2}{J_\omega}+\frac{V_{2B}^2(\rho_z)}{8} < \frac{\{\beta-(y+\rho_z)\}^2}{8}$, then it is not profitable for M to add an I4I channel, she continues with the production of traditional product, and her optimal decision is equal to that of period $P = 1$.
   (2) Otherwise, it is profitable for M to produce I4I product in addition to the traditional product; in this case, M's optimal traditional product wholesale price is: $[w_{2B}^*]_{AW} = y+\frac{4\mu\{V_{2B}(\rho_z)+\delta V_I(\rho_z)\}}{J_\omega} - \frac{(\lambda^2/2)V_{2B}(\rho_z)}{J_\omega}$, optimal I4I product wholesale price is: $[w_I^*]_{AW} = y+\frac{4\mu\{V_I(\rho_z)+\delta V_{2B}(\rho_z)\}}{J_\omega}$, and optimal innovation level is: $[\eta^*]_{AW} = \frac{\lambda}{J_\omega}\{V_I(\rho_z)+\delta V_{2B}(\rho_z)\}$.

b. *The retailer R's optimal decisions are characterized as follows: (i) in period $P = 1$, her optimal order quantity is: $[d_{1B}^*]_{AW} = \frac{\beta-(y+2z-\rho_z)}{4}$; (ii) in period $P = 2$, either of the following two happens:*
   (1) If M does not add an I4I channel, then R's optimal decision is equal to that of $P = 1$.
   (2) If M adds an I4I channel, then R's optimal traditional product order quantity is: $[d_{2B}^*]_{AW} = \frac{V_{2Bz'}}{4}$ and optimal I4I product order quantity is: $[d_I^*]_{AW} = \frac{V_{Iz'}}{4} + \frac{\lambda^2\{V_I(\rho_z)+\delta V_{2B}(\rho_z)\}}{4J_\omega}$, where $V_i(\rho_z) = \beta\phi_i-(1-\delta)(y+\rho_z)$, $V_{iz'} = V_i(\rho_z)-2(1-\delta)(z-\rho_z)$, $i = \{I,2B\}$, $J_\omega = 8\mu(1-\delta^2)-\lambda^2$, and $\rho_z = \int_{\underline{z}}^{\overline{z}} z d\{G(z)\}$.

From Theorem 3, we observe that in period $P = 2$, the manufacturer M's total profit condition for incorporating I4I production: $\frac{\mu\{V_I(\rho_z)+\delta V_{2B}(\rho_z)\}^2}{J_\omega}+\frac{V_{2B}^2(\rho_z)}{8} > \frac{\{\beta-(y+\rho_z)\}^2}{8}$ depends upon the retailer $R's$ expected cost: ρ_z. When M accurately estimates R's unit cost: $\rho_z = z$, the condition for incorporating I4I production is the same under both full and asymmetric information.

As M calculates her optimal decisions for both periods based on her estimate of R's cost instead of the actual value, this leads to deviation in the optimal parameter calculation of M. In period $P = 1$, M's wholesale price changes by: $[w_{1B}^*]_{AW} - [w_{1B}^*]_{FW} = \frac{z-\rho_z}{2}$. Due to this price difference, the retailer R's order quantity in period $P = 1$ changes by: $[d_{1B}^*]_{AW} - [d_{1B}^*]_{FW} = \frac{\rho_z-z}{4}$. This analysis of period $P = 1$ matches with the findings in prior studies (Biswas et al., 2016; Corbett & Tang, 1999). Due to the said usage of the retailer R's expected cost in period $P = 2$, the manufacturer's wholesale price of I4I product changes by: $[w_I^*]_{AW} - [w_I^*]_{FW} = \frac{4\mu}{J_\omega}(1-\delta^2)(z-\rho_z)$, the wholesale price of traditional product changes by: $[w_{2B}^*]_{AW} - [w_{2B}^*]_{FW} = \frac{\{4\mu-(\lambda^2/2)\}}{J_\omega}(1-\delta^2)(z-\rho_z)$, and her innovation level changes by: $[\eta^*]_{AW} - [\eta^*]_{FW} = \frac{\lambda}{J_\omega}(1-\delta^2)(z-\rho_z)$.

Corollary 1. *As the manufacturer M does not know the retailer R's per unit cost z and yet makes her optimal contract decision in $P = 2$ based on her prior belief $G(z)$, R's optimal decisions change as follows: (1) I4I product order quantity changes by $[d_I^*]_{AW} - [d_I^*]_{FW} = \frac{(1-\delta)}{4J_\omega}(\rho_z - z)\{8\mu(1-\delta^2) - \delta\lambda^2\}$ and (2) traditional product order quantity changes by: $[d_{2B}^*]_{AW} - [d_{2B}^*]_{FW} = \frac{(1-\delta)}{4}(\rho_z - z)$, where $\rho_z = \int_{\underline{z}}^{\bar{z}} zd\{G(z)\}$.*

From Corollary 1, we understand the following. If the manufacturer M's estimate of retailer R's cost is higher than the actual cost: $\rho_z > z$, then M charges lower wholesale prices for both I4I and traditional products. As a result, R's order quantities for both I4I and traditional products increase: (1) $[d_I^*]_{AW} > [d_I^*]_{FW}$ and (2) $[d_{2B}^*]_{AW} > [d_{2B}^*]_{FW}$. This interpretation, as derived from the analysis of asymmetric information game in the presence of M's strategic decision to incorporate I4I product in period $P = 2$, is unreported in the extant literature. Under asymmetric information, the optimal I4I product introduction strategy of the manufacturer is presented below through Proposition 4.

Proposition 4. *Manufacturer M's I4I product introduction strategy, under asymmetric information, is as follows: (i) If $\phi_I < [\bar{\phi}_I]_{AW}$, then M should not introduce I4I product as her profit decreases in ϕ_I; (ii) If $[\bar{\phi}_I]_{AW} < \phi_I < [\bar{\bar{\phi}}_I]_{AW}$, then M should introduce I4I product in the market even though her profit would be less compared to the situation where the I4I product is not introduced; (iii) If $\phi_I > [\bar{\bar{\phi}}_I]_{FW}$, then M must introduce I4I product in the market as introduction of I4I product ensures higher profitability, where $[\bar{\phi}_I]_{AW} = \frac{8\mu(1-\delta)-(\lambda^2/\beta)[\beta-(y+\rho_z)(1-\delta)]}{16\mu(1-\delta)-\lambda^2}$ and $[\bar{\bar{\phi}}_I]_{AW} = \frac{1}{\beta(1-\delta)}\left[\sqrt{\frac{8\mu(1-\delta^2)-\lambda^2}{8\mu}}[\beta-(y+\rho_z)] - [\beta\delta-(y+\rho_z)(1-\delta^2)]\right]$.*

From Proposition 4 and Proposition 2, we realize that when M's estimation of R's marginal cost is equal to R's actual marginal cost, M's optimal product introduction strategies under full and asymmetric information are the same. When M's estimation of R's marginal cost is less than R's actual marginal cost: $\rho_z < z$, the market potential threshold of the I4I product for achieving overall profit by adding an I4I product line would be higher in asymmetric information compared to the full information case: $[\bar{\bar{\phi}}_I]_{AW} > [\bar{\bar{\phi}}_I]_{FW}$. The information asymmetry of R's marginal cost results in reduced overall profits in the supply chain. Hence, the market potential threshold of the I4I product would be higher in asymmetric information compared to the full information case.

We present the retailer's pricing strategies for period $P = 2$ in the proposition below.

Proposition 5. *When manufacturer M introduces I4I product in $P = 2$ under asymmetric information, then the retailer R's optimal I4I product retail price is: $[p_I^*]_{AW} = (y + 2z - \rho_z) + \frac{3\{4\mu(V_{Iz'}+\delta V_{2Bz'})+\lambda^2(z-\rho_z)\}}{2\{8\mu(1-\delta^2)-\lambda^2\}}$, optimal traditional product retail price is: $[p_{2B}^*]_{AW} = (y + 2z - \rho_z) + \frac{3\{4\mu(V_{2Bz'}+\delta V_{Iz'})-(\lambda^2/2)V_{2Bz'}+\lambda^2\delta(z-\rho_z)\}}{2\{8\mu(1-\delta^2)-\lambda^2\}}$, market share of I4I product is: $\frac{\frac{1}{V_{2Bz'}}\left[V_{Iz'}+\frac{\lambda^2}{J_\omega}\{V_I(\rho_z)+\delta V_{2B}(\rho_z)\}\right]}{1+\frac{1}{V_{2Bz'}}\left[V_{Iz'}+\frac{\lambda^2}{J_\omega}\{V_I(\rho_z)+\delta V_{2B}(\rho_z)\}\right]}$, and market share of traditional product is: $\frac{1}{1+\frac{1}{V_{2Bz'}}\left[V_{Iz'}+\frac{\lambda^2}{J_\omega}\{V_I(\rho_z)+\delta V_{2B}(\rho_z)\}\right]}$, where $V_i(\rho_z) = \beta\phi_i - (1-\delta)(y+\rho_z)$, $V_{iz'} = V_i(\rho_z) - 2(1-\delta)z$, $i = \{I, 2B\}$, $J_\omega = 8\mu(1-\delta^2) - \lambda^2$, and $\rho_z = \int_{\underline{z}}^{\bar{z}} zd\{G(z)\}$.*

From Proposition 5, we can drive the difference of retail prices of traditional and I4I products: $[p_I^*]_{AW} - [p_{2B}^*]_{AW} = \frac{3}{2}\left[\frac{4\mu}{J_\omega}(1-\delta)(V_{Iz'} - V_{2Bz'}) + \frac{\lambda^2}{2J_\omega}V_{2Bz'} - \frac{\lambda^2(z-\rho_z)(1-\delta)}{J_\omega}\right]$. From these expressions, we realize that in the end market, the price of I4I product would be higher than the traditional product provided the following conditions are satisfied: $V_{Iz'} > V_{2Bz'}$ and $c < \rho_z$.

Similarly, the wholesale price of I4I product would be higher than the traditional product's: $[w_I^*]_{AW} > [w_{2B}^*]_{AW}$, provided that the market potential of I4I product exceeds the following threshold: $\phi_I > [\bar{\phi}_I]_{AW}$. At equal market potential: $\phi_I = \phi_{2B}$, I4I product would be priced higher than traditional product: $[p_I^*]_{AW} > [p_{2B}^*]_{AW}$, and the demand for I4I product would be higher than the traditional product's: $[d_I^*]_{AW} > [d_{2B}^*]_{AW}$.

4.3. Value of information

The presence of asymmetric information A in the SC results in the redistribution of profits between the SC members. Under full information F, the manufacturer M gains an extra profit known as the value of information $[VoI]$, by being better informed about the retailer R's cost: z, compared to asymmetric information. Therefore, the value of information represents the maximum amount that M is willing to spend to gather R's accurate cost information. Using W contract, we drive M's value of information as: $[VoI]_{P=i} = E_z([\pi_{iM}^*]_{FW,P=i} - [\pi_{iM}^*]_{AW,P=i})$, $i = \{1,2\}$ for both periods $P = 1$ and $P = 2$ and present in the proposition below.

Proposition 6. *When manufacturer M uses W contract, her values of information $[VoI]$ are given as: (i) M's $[VoI]$ for period $P = 1$ is: $[VoI]_{P=1} = \frac{Var(z)}{8}$, and (ii) M's $[VoI]$ for period $P = 2$ is: $[VoI]_{P=2} = \frac{Var(z)}{8}\left[\frac{(1-\delta)^2\{16\mu(1+\delta)-\lambda^2\}}{8\mu(1-\delta^2)-\lambda^2}\right]$.*

From Proposition 6, we observe that in period $P = 2$, M's expected profit would increase by $\frac{Var(z)}{8}\left[\frac{(1-\delta)^2\{16\mu(1+\delta)-\lambda^2\}}{J_\omega}\right]$ if she is fully informed about R's cost z. $[VoI]_{P=2}$ depends upon the variance of the distribution of z, competition between I4I and traditional products δ, Industry 4.0 innovation investment parameter μ, and consumer sensitivity to I4I product λ. From this expression of $[VoI]_{P=2}$, we realize that it increases in Industry 4.0 innovation sensitivity of consumers and decreases in both Industry 4.0 innovation investment and competition. By comparing the values of $[VoI]_{P=1}$ and $[VoI]_{P=2}$, we understand that M's $[VoI]$ in period $P = 2$ increases when the competition between I4I and traditional product is sufficiently small: $\delta < \frac{1}{2}$.

4.4. Impact of individual rationality constraints

In this section, we explore the individual rationality constraint's effect on the supply chain decisions of the manufacturer M and the retailer R in the period $P = 2$. As the analysis of individual rationality constraint on M's optimization problem of period $P = 1$ is well studied in the literature (Biswas et al., 2016; Corbett & Tang, 1999), we ignore this analysis in our discussion. When the profit of M (R) falls below her minimum profit level, also known as reservation profit level (RP), she would no longer be monetarily incentivized to trade with R (M). From Theorem 2, we realize that both M's and R's profits are decreasing in R's cost z. Thus, individual rationality constraints restrict the trading opportunities of the supply chain agents. In such cases, contract cessation policies, based on R's cost z, can be formulated for both M and R (Corbett & Tang, 1999). The contract cessation point is the highest cost beyond which the supply chain agent is not interested in engaging in the contract. When the cessation point $\mathring{z}$ is exceeded, the supply chain agent's profit is below the RP, and hence, she would be disincentivized to become the contract partner. We present the contract cessation points (CCP) for the wholesale price contract in the proposition below.

Proposition 7. *When the manufacturer M uses W contract to trade with the retailer R in period $P = 2$, the CCPs are drived as follows: (i)*

M's CCP is: $[\mathring{z}_{2M}]_{FW} = -y + \frac{\beta\delta\mu+\beta\phi_I\mu+\beta\phi_{2B}(\mu-\frac{\lambda^2}{8})-\sqrt{\Delta_{2M}^{FW}}}{(2\mu(1+\delta)-\frac{\lambda^2}{8})(1-\delta)}$ *(ii) R's CCP for traditional product is:* $[\mathring{z}_{2R2B}]_{FW} = -y + \frac{\beta\delta\mu+\beta\phi_{2B}(2\mu-\frac{\lambda^2}{4})-\sqrt{\Delta_{2R2B}^{FW}}}{(2\mu(1+\delta)-\frac{\lambda^2}{4})(1-\delta)}$, *and (iii) R's CCP for I4I product is:* $[\mathring{z}_{2RI}]_{FW} = -y + \frac{2\beta\mu\lambda^2(\delta+\phi_{2B}\delta^2+\phi_I)+AJ_\omega\mu(\delta+2\phi_I)-J_\omega\sqrt{\Delta_{2RI}^{FW}}}{2\mu(1-\delta^2)(\lambda^2(1+\delta)+J_\omega)}$, *where* $\Delta_{2M}^{FW} = [J_\omega\overline{\pi}_{2M}(2\mu(1+\delta)-\frac{\lambda^2}{8})] + [A^2(\phi_{2B}-\phi_I)^2(\delta^2\mu^2-\mu(\mu-\frac{\lambda^2}{8}))]$, $\Delta_{2RI}^{FW} = [\overline{\pi}_{2RI}8\mu(1+\delta)(\lambda^2(1+\delta)+J_\omega)] + [A^2\delta^2\mu^2(\phi_{2B}-\phi_I)^2]$, $\Delta_{2R2B}^{FW} = [J_\omega\overline{\pi}_{2R2B}(8\mu(1+\delta)-\lambda^2)] + [A^2\delta^2\mu^2(\phi_{2B}-\phi_I)^2]$ *and* $J_\omega = 8\mu(1-\delta^2)-\lambda^2$.

From Proposition 7, we observe that the manufacturer's contract cessation point $[\mathring{z}_{2M}]_{FW}$ is increasing in competition between I4I and traditional products δ, consumer sensitivity to I4I product λ, and decreasing in Industry 4.0 innovation investment parameter μ. The aforementioned contract cessation points: $[\mathring{z}_{2M}]_{FW}, [\mathring{z}_{2R2B}]_{FW}$, and $[\mathring{z}_{2RI}]_{FW}$, decrease in manufacturer's marginal cost y. Next, we are going to analyze channel-coordination in this context.

4.5. Analysis of channel coordinating contract

In this sub-section, we analyze the effect of a channel coordinating L contract on the manufacturer M's strategic decision-making process. We consider that in period $P = 1$, M sells her product to R using a transfer payment function of the following structure: $w_{1B}d_{1B} + T_{1B}.1_{[d_{1B}>0]}$ and in period $P = 2$, M sells I4I and traditional products to R using two separate transfer payment functions: $w_I d_I + T_I.1_{[d_I>0]}$ and $w_{2B}d_{2B} + T_{2B}.1_{[d_{2B}>0]}$ respectively where $1_{[d_i>0]} = [1$ if $d > 0$ and $i = \{1B, 2B, I\}]$. R agrees to enter into a contract with M iff her individual rationality constraints are satisfied in both periods as follows: (i) in period $P = 1$, $\pi_{1R1B}(d_{1B}) \geq \overline{\pi}_{1R1B}$ and (ii) in period $P = 2$, $\pi_{2R2B}(d_{2B}) \geq \overline{\pi}_{2R2B}$ and $\pi_{2RI}(d_I) \geq \overline{\pi}_{2RI}$. M solves her optimization problem, while satisfying R's individual rationality constraints in both periods. We present our results in Theorem 4 below.

Theorem 4.

a. *When the manufacturer M uses L contracts in both periods, her optimal decisions are characterized as follows: (i) in period $P = 1$, M's optimal per unit price is: $[w^*_{1B}]_{FL} = y$, and optimal franchise fee is: $T_{1B} = \frac{1}{4}\{\beta-(y+z)\}^2 - \bar{\pi}_{1R}$ (ii) in period $P = 2$, either of the following two happens:*
(1) If $\frac{\mu(V_I+\delta V_{2B})^2}{J} + \frac{V_{2B}^2}{4} - \overline{\pi}_{2RI} < \frac{(\beta-(y+z))^2}{4}$, then it is not profitable for M to add an I4I channel, she continues with the production of traditional products, and her optimal decision is equal to that of period $P = 1$;
(2) Otherwise, it is profitable for M to produce I4I product in addition to the traditional product; in this case, M's optimal traditional product per unit price is: $[w^*_{2B}]_{FL} = y$, and optimal traditional product franchise fee is: $T_{2B} = \{[\beta\phi_{2B}(1-\delta)-(w_{2B}+z)(1-\delta^2)+\beta\delta+\delta\lambda\eta]/2(1-\delta^2)\}\{[\beta\phi_{2B}-(w_{2B}+z)+(w_I+z)\delta]/2\} - \overline{\pi}_{2R2B}$, optimal I4I product per unit price is: $[w^*_I]_{FL} = y$, optimal I4I product franchise fee is: $T_I = \{[\beta\phi_I(1-\delta)-(w_I+z)(1-\delta^2)+\beta\delta+\lambda\eta]/2(1-\delta^2)\}\{[\beta\phi_I-(w_I+z)+(w_{2B}+z)\delta+\lambda\eta]/2\} - \overline{\pi}_{2RI}$ and optimal innovation level is: $[\eta^*]_{FL} = \frac{\lambda}{J}(V_I+\delta V_{2B})$.

b. *The retailer R's optimal decisions are characterized as follows: (i) in period $P = 1$, her optimal order quantity is: $[d^*_{1B}]_{FL} = \frac{\beta-(y+z)}{2}$, (ii) in period $P = 2$, either of the following two happens:*
(1) If M does not add an I4I channel, then R's optimal decision is equal to that of $P = 1$;
(2) If M adds an I4I channel, then R's optimal traditional product order quantity is: $[d^*_{2B}]_{FL} = \frac{V_{2B}}{2}$, optimal I4I product order quantity is: $[d^*_I]_{FL} = \frac{V_I}{2} + \frac{(\lambda^2/4)(V_I+\delta V_{2B})}{J}$, and she earns her reservation profits in both periods, where $V_i = [\beta\phi_i-(1-\delta)(y+z)], i = \{I, 2B\}$, and $J = 4\mu(1-\delta^2)-\lambda^2$.

From Theorem 4, we observe M's criterion for incorporating the I4I production in period $P = 2$ includes R's I4I channel reservation profit. When R's I4I channel reservation profit is higher, incorporation of the I4I product becomes difficult for M. We realize that M sets the wholesale price for both products equivalent to her marginal cost: $[w^*_I]_{FL} = [w^*_{2B}]_{FL} = y$. M gains its entire profit by charging franchise fees: T_{1B} in $P = 1$, and T_I and T_{2B} in $P = 2$ from R and R is earning its channel-specific reservation profits.

Using Theorem 2 and Theorem 4, we compare R's optimal order quantity decisions and M's optimal innovation decision of period $P = 2$ between the FW and FL cases, and we present the results below.

Corollary 2. *(i) M's optimal product innovation level changes by: $[\eta^*]_{FL} - [\eta^*]_{FW} = \frac{4\mu\lambda(V_I+\delta V_{2B})(1-\delta^2]}{JJ_\omega} > 0$, (ii) R's optimal I4I product order quantity changes by: $[d^*_I]_{FL} - [d^*_I]_{FW} = \frac{V_I}{4} + \frac{(\lambda^2/4)(V_I+\delta V_{2B})(12\mu(1-\delta^2)-\lambda^2)}{JJ_\omega} > 0$, and (iii) R's optimal traditional product order quantity changes by: $[d^*_{2B}]_{FL} - [d^*_{2B}]_{FW} = \frac{V_{2B}}{4} > 0$; where $V_i = [\beta\phi_i-(1-\delta)(y+z)], i = \{I, 2B\}$, $J = 4\mu(1-\delta^2)-\lambda^2$, and $J_\omega = 8\mu(1-\delta^2)-\lambda^2$.*

From Corollary 2, we observe that, compared to the W contract, the equilibrium order quantity of both products would be higher in the L contract: $[d^*_I]_{FL} > [d^*_I]_{FW}$ and $[d^*_{2B}]_{FL} > [d^*_{2B}]_{FW}$. We further understand that in full information, the manufacturer would be exerting higher optimal innovation efforts in the L contract than in the W contract: $[\eta^*]_{FL} > [\eta^*]_{FW}$. We present the retailer's pricing strategies in the proposition below.

Proposition 8. *L contract results in perfect coordination in period $P = 2$, as evident from the following: $[p^*_I]_{FL} = [p^*_I]_C$, $[p^*_{2B}]_{FL} = [p^*_{2B}]_C$, $[d^*_I]_{FL} = [d^*_I]_C$, and $[d^*_{2B}]_{FL} = [d^*_{2B}]_C$.*

From Proposition 8, we understand that L contract coordinates the entire SC: (i) R's pricing and order quantity decisions and M's innovation level decision in L contract are equal to those of a central planner. (ii) The overall profit of the SC in L contract is the same as that of the central planner. From Proposition 8, we further understand that firms should adopt long-term contractual agreements to enhance profitability while adopting the I4I production process. For instance, Arvind Limited has entered into a long-term agreement with GAP (her downstream customer) for the adoption of Industry 4.0 technology (Section 1.1). For similar reasons, ABFRL has also partnered with IBM cloud services (BusinessStandard, 2018).

Using Proposition 3 and Proposition 8, we compare R's pricing strategies between the FW and FL cases. The difference in the I4I product's retail price is: $[p^*_I]_{FW} - [p^*_I]_{FL} = \frac{4\mu(V_I+\delta V_{2B})[2\mu(1-\delta^2)-\lambda^2]}{JJ_\omega}$, and the difference in the retail price of the traditional product is: $[p^*_{2B}]_{FW} - [p^*_{2B}]_{FL} = \frac{4\mu(V_{2B}+\delta V_I)[2\mu(1-\delta^2)-\lambda^2]}{JJ_\omega} + \frac{(\lambda^2 V_{2B}/4)[4\mu(1-\delta^2)+\lambda^2]}{JJ_\omega}$. For I4I product, we find that if $2\mu(1-\delta^2) > \lambda^2$, the retail price in W contract would be higher than the retail price in L contract: $[p^*_I]_{FW} > [p^*_I]_{FL}$. With L contract, we discuss the optimal product introduction strategy of M in Proposition 9 below.

Proposition 9. *In period $P = 2$, M's optimal product introduction strategy is as follows: (i) when $\phi_I < [\bar{\phi}_I]_{FL}$, then M should not introduce I4I product in the market as her profit decreases in market potential ϕ_I, (ii) when $[\bar{\phi}_I]_{FL} < \phi_I < [\bar{\bar{\phi}}_I]_{FL}$, then M should introduce I4I product in the market though her profit would be less compared to the situation where it is not introduced, and (iii) when $\phi_I > [\bar{\bar{\phi}}_I]_{FL}$, then M must introduce I4I product in the market as her overall profit would be more than the case where it is not introduced; where, $[\bar{\phi}_I]_{FL} = \frac{4\mu(1-\delta)-(\lambda^2/\beta)[\beta-(y+z)(1-\delta)]}{8\mu(1-\delta)-\lambda^2}$ and $[\bar{\bar{\phi}}_I]_{FL} = \frac{1}{\beta(1-\delta)}\left[\sqrt{\frac{(4\mu(1-\delta^2)-\lambda^2)[\beta-(y+z)+\overline{\pi}_{2RI}]}{4\mu}} - [\beta\delta-(y+z)(1-\delta^2)]\right]$.*

From Propositions 1 and 9, we observe that the following market potential threshold of I4I product: $[\bar{\phi}_I]$, is equal in both L contract and the centralized case: $[\bar{\phi}_I]_{FL} = [\bar{\phi}_I]_C$, as L contract coordinates the aforementioned supply chain. Similarly, when R has no reservation profit for the I4I product: $\overline{\pi}_{2RI} = 0$, the market potential threshold of the I4I product, for gaining high overall profit is the same in both L contract and the centralized case: $[\bar{\bar{\phi}}_I]_{FL} = [\bar{\bar{\phi}}_I]_C$.

Under the asymmetric information setting, M has to ensure that R's individual rationality constraints are always satisfied. As R's profit decreases in her own unit cost z, these constraints have to be met over the entire range of z (Corbett & Tang, 1999). Therefore, individual rationality constraints of R are required to be satisfied at the highest possible value of z: $z = \overline{z}$. We use this argument to solve M's optimization problem under the asymmetric information setting and it is reported in Appendix.

Theorem 5. *In asymmetric information setting, where manufacturer M uses L contract in both periods,*

a. *Manufacturer's optimal decisions are as follows: (i) in period $P = 1$, the optimal per unit price is: $[w^*_{1B}]_{AL} = y+\overline{z}-\rho_z$, (ii) in period $P = 2$, either of the following two happens:*
(1) If $\frac{\mu(V_{I\hat{z}}+\delta V_{2B\hat{z}})^2}{J} + \frac{V^2_{2B\hat{z}}}{4} - \overline{\pi}_{2RI} + \mathbb{R} < \frac{(\beta-(y+2\overline{z}-\rho_z))^2}{4} + \frac{(\overline{z}-\rho_z)(\beta-(y+\overline{z}))}{2}$, then it is not profitable for M to add an I4I channel, M continues to produce only traditional products, and M's optimal decisions in $P = 2$ are equal to those of $P = 1$.
(2) If $\frac{\mu(V_{I\hat{z}}+\delta V_{2B\hat{z}})^2}{J} + \frac{V^2_{2B\hat{z}}}{4} - \overline{\pi}_{2RI} + \mathbb{R} > \frac{(\beta-(y+2\overline{z}-\rho_z))^2}{4} + \frac{(\overline{z}-\rho_z)(\beta-(y+\overline{z}))}{2}$, then it is profitable for M to produce an I4I product along with traditional product, M's per unit price of traditional product is: $[w^*_{2B}]_{AL} = y+\overline{z}-\rho_z$, M's per unit price of an I4I product is: $[w^*_I]_{AL} = y + \overline{z} - \rho_z$, and M's innovation level is: $[\eta^*]_{AL} = \frac{\lambda}{J_\omega}(V_{I\overline{z}} + \delta V_{2B\overline{z}})$.
b. *Retailer's optimal decisions are as follows: (i) in $P = 1$, R's optimal order quantity is: $[d^*_{1B}]_{AL} = \frac{\beta-(y+\overline{z}+z-\rho_z)}{2}$, (ii) in $P = 2$ either of the following two happens:*
(1) If M does not add an I4I product line, R's optimal decision is equal to that of $P = 1$.
(2) If M adds an I4I product line, R's optimal traditional product order quantity is: $[d^*_{2B}]_{AL} = \frac{V_{2B\overline{z}'}}{2}$, and R's optimal I4I product order quantity: $[d^*_I]_{AL} = \frac{V_{I\overline{z}'}}{2} + \frac{(\lambda^2/2)(V_{I\overline{z}}+\delta V_{2B\overline{z}})}{J}$, where $V_i(\rho_z) = \beta\phi_i - (1-\delta)(y+\rho_z)$, $V_{i\overline{z}} = V_i(\rho_z) - (1-\delta)(\overline{z}-\rho_z)$, $V_{iz'} = V_i(\rho_z) - 2(1-\delta)(z-\rho_z)$, $V_{i\overline{z}'} = V_i(\rho_z) - (1-\delta)(y+\overline{z}-2\rho_z)$, $V_{i\hat{z}} = V_i(\rho_z) - 2(1-\delta)(\overline{z}-\rho_z)$, $i = \{I, 2B\}$, $J = 4\mu(1-\delta^2) - \lambda^2$, $J_\omega = 8\mu(1-\delta^2) - \lambda^2$, $\rho_z = \int_{\underline{z}}^{\overline{z}} zd\{G(z)\}$, and $\mathbb{R} = (\overline{z} - \rho_z)\left[(\lambda^2/4J)\left[(V_{I\hat{z}} + \delta V_{2B\hat{z}}) + (V_{I\overline{z}} + \delta V_{2B\overline{z}})\right] + (V_{I\overline{z}} + V_{2B\overline{z}})/2\right]$.

By comparing the results of Theorem 5 with those of Theorem 4, we realize that the optimal results and M's criterion for adding I4I production in period $P = 2$ under full information are a particular case of the generalized information asymmetry results. The optimal results for the full information case can be obtained from Theorem 5 by using the criterion: $\underline{z} = \overline{z} = \rho_z$. From Theorem 5, we also observe that M's per unit price is a summation of her marginal cost: y, and a markup price: $\overline{z} - \rho_z$. Under asymmetric information, M protects herself against the variability of the retailer's cost by charging $\overline{z}-\rho_z$ extra as this expression represents R's right-hand cost variability from the mean. Due to this reason, in the AL case, the manufacturer accepts a lower franchise fee to ensure the retailer's minimum profit is met.

Similarly, we compare the difference in optimal quantities of both products under the full and asymmetric information game. When both the products have the same market potential: $\phi_I = \phi_{2B}$, the difference in optimal quantities would be higher under full information: $([d^*_I]_{FL} - [d^*_{2B}]_{FL}) - ([d^*_I]_{AL} - [d^*_{2B}]_{AL}) = \frac{\lambda^2(1-\delta^2)(\overline{z}-z)}{2J} > 0$; this implies that the sale of I4I product compares to traditional product is more under full information game. The difference in optimal quantity of the products is: $[d^*_I]_{AL} - [d^*_{2B}]_{AL} = \frac{\lambda^2(1+\delta)V_{I\overline{z}}}{2J}$. The optimal order quantity of traditional products under full and asymmetric information changes by: $[d^*_{2B}]_{FL} - [d^*_{2B}]_{AL} = \frac{(1-\delta)(\overline{z}-\rho_z)}{2}$. In L contract, the optimal order quantity of traditional product would be higher under full information than asymmetric information: $[d^*_{2B}]_{FL} > [d^*_{2B}]_{AL}$, for $\rho_z \neq \overline{z}$.

By comparing the results of Theorem 5 with those of Theorem 3, we observe in the asymmetric information case, the traditional product's order quantity would be more in L contract than in W contract: $[d^*_{2B}]_{AL} - [d^*_{2B}]_{AW} = \frac{V_{2B\hat{z}}}{4}$. From Theorem 2, 3, 4, and 5, we further realize that the traditional channel's optimal order quantity $[d^*_{2B}]$ is independent of consumer innovation sensitivity λ in all the four decentralized cases.

By comparing the results of Theorem 5 with those of Theorem 4, we examine the manufacturer's innovation efforts under full and incomplete information. The optimal product innovation level would be higher in full information than asymmetric information: $[\eta^*]_{FL} > [\eta^*]_{AL}$, for $z \neq \overline{z}$. The difference in the optimal product innovation level is: $[\eta^*]_{FL} - [\eta^*]_{AL} = \frac{\lambda(1-\delta^2)(\overline{z}-z)}{J}$. Under asymmetric information, the optimal innovation effort $[\eta^*]_{AL}$ is independent of the actual retailer's cost z but depends upon its upper limit $\overline{z}$. We present the retailer R's pricing strategies in the proposition below.

Proposition 10. *Under asymmetric information setting, when M uses L contract and introduces I4I product in period $P = 2$, then R's optimal retail price for I4I product is: $p_I^{AL*} = (y+\overline{z}+z-\rho_z) + \frac{[\lambda^2(z-\rho_z)]}{2J} + \left[\frac{2\mu(V_{I\overline{z}'}+\delta V_{2B\overline{z}'})}{J}\right]$, and optimal retail price for traditional product is: $p_{2B}^{AL*} = (y+\overline{z}+z-\rho_z) + \frac{[\lambda^2\delta(z-\rho_z)]}{2J} + \left[\frac{2\mu(V_{2B\overline{z}'}+\delta V_{I\overline{z}'})}{J} - \frac{(\lambda^2/2)V_{2B\overline{z}'}}{J}\right]$, where $V_{i\overline{z}'} = V_i(\rho_z) - (1-\delta)(y + \overline{z} - 2\rho_z)$, $V_i(\rho_z) = \beta\phi_i - (1-\delta)(y+\rho_z)$, $i = \{I, 2B\}$, $J = 4\mu(1-\delta^2) - \lambda^2$, and $\rho_z = \int_{\underline{z}}^{\overline{z}} zd\{G(z)\}$.*

By comparing the results of Proposition 8 with those of Proposition 10, we obtain the difference in optimal prices of both the products under full and incomplete information. When both products have the same market potential: $\phi_I = \phi_{2B}$, the difference in optimal retail prices would be higher under full information: $([p^*_I]_{FL} - [p^*_{2B}]_{FL}) - ([p^*_I]_{AL} - [p^*_{2B}]_{AL}) = \frac{(\lambda^2/2)(1-\delta)(\overline{z}-z)}{J}$. Similarly, under asymmetric information, at the equal market potential: $\phi_I = \phi_{2B}$, the price of I4I product would be more than the traditional product. The difference in optimal price of the products is: $[p^*_I]_{AL} - [p^*_{2B}]_{AL} = \frac{\lambda^2 V_{2B\overline{z}}}{2J}$. We present the numerical analysis of the optimal values of the L contract in Appendix E of Online Supplementary Material.

4.6. Manufacturer's contract cessation policy for channel coordinating contract

We present below the contract cessation points (CCPs) of both the manufacturer (M) and the retailer (R) when M uses the channel coordinating contract, as discussed in Section 4.5.

Proposition 11. *M's CCP is $[\mathring{z}_{2M}]_{FL} = -y + \frac{\beta\delta\mu+\beta\phi_I\mu+\beta\phi_{2B}(\mu-\frac{\lambda^2}{4})-\sqrt{\Delta^{FL}_{2M}}}{(2\mu(1+\delta)-\frac{\lambda^2}{4})(1-\delta)}$, where $\Delta^{FL}_{2M} = [J\overline{\pi}_{2M}(2\mu(1+\delta) - \frac{\lambda^2}{4})] + [A^2(\phi_{2B} - \phi_I)^2(\delta^2\mu^2 - \mu(\mu - \frac{\lambda^2}{4}))]$ and $J = 4\mu(1-\delta^2) - \lambda^2$, and R does not have a CCP.*

From Proposition 11, we observe that the manufacturer's contract cessation point $[\mathring{z}_{2M}]_{FL}$ is increasing in competition between I4I and traditional products δ, consumer sensitivity to I4I product λ, and decreasing in Industry 4.0 innovation investment parameter μ.

5. Numerical analysis

In this section, we perform a numerical analysis to investigate variations in optimal supply chain parameters with a change in retailers' costs. For this purpose, we consider: (i) total market potential, $\beta = 400$, (ii) market potential of both I4I and traditional products are equal in period $P = 2$, $\phi_I = \phi_{2B} = \frac{1}{2}$; therefore, market potentials of I4I and traditional products are: $\beta\phi_I = \beta\phi_{2B} = 200$, (iii) consumer innovation

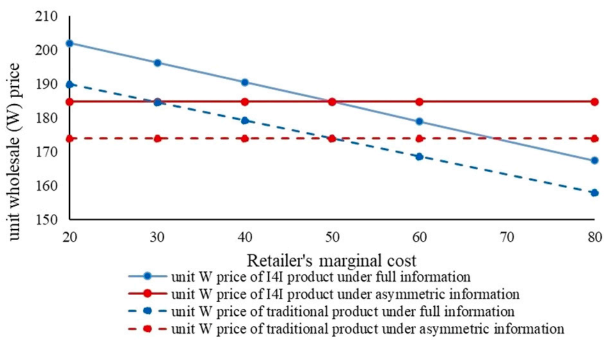


Fig. 2. Unit wholesale price v/s Retailer's marginal cost in W contract.

sensitivity, $\lambda = 3$, (iv) manufacturer M's marginal cost, $y = 50$, (v) innovation investment parameter, $\mu = 10$, (vi) cross-price sensitivity, $\delta = 0.4$, (vii) retailer R's reservation profit for I4I product, $\overline{\pi}_{RI} = 1000$, and (viii) R's reservation profit for the traditional product, $\overline{\pi}_{RB} = 700$. We consider R's cost in the following way: $z \in [20, 80]$ with mean, $\rho_z = 50$. These assumptions are in line with extant literature (Corbett & Tang, 1999; Ghosh & Shah, 2012) and satisfy the conditions of joint concavity.

In Fig. 2, we compare the I4I and traditional products' wholesale prices under full and incomplete information. We observe that the I4I product's wholesale price is more than the traditional product's wholesale price under both full and incomplete information: $[w_I^*]_{FW} > [w_{2B}^*]_{FW}$ and $[w_I^*]_{AW} > [w_{2B}^*]_{AW}$. Under incomplete information, the wholesale price depends on the expected value of R's cost: ρ_z and not on its actual value: z. This results in the wholesale price remaining constant with a change in R's cost. When $\rho_z = z$, the optimal wholesale prices satisfy the following relations: $[w_I^*]_{FW} = [w_I^*]_{AW}$ and $[w_{2B}^*]_{FW} = [w_{2B}^*]_{AW}$.

In Fig. 3(a) and 3(b), we analyze the variation of M's and R's unit margins, respectively. We observe that in both full and asymmetric information cases, M's unit margin from the I4I product is higher than the traditional product: $[m_{2MI}^*]_{FW} > [m_{2M2B}^*]_{FW}$ and $[m_{2MI}^*]_{AW} > [m_{2M2B}^*]_{AW}$. We observe a similar pattern for R's unit margin: $[m_{2RI}^*]_{FW} > [m_{2R2B}^*]_{FW}$ and $[m_{2RI}^*]_{AW} > [m_{2R2B}^*]_{AW}$. When M's expected value of R's cost is less than its actual cost: $\rho_z > z$, (i) M's unit margin is higher in full information than incomplete information: $[m_{2MI}^*]_{FW} > [m_{2MI}^*]_{AW}$ and $[m_{2M2B}^*]_{FW} > [m_{2M2B}^*]_{AW}$, and (ii) R's unit margin is lower in full information than incomplete information: $[m_{2RI}^*]_{FW} < [m_{2RI}^*]_{AW}$ and $[m_{2R2B}^*]_{FW} < [m_{2R2B}^*]_{AW}$. When $\rho_z = z$, M's and R's unit margins satisfy the following relations: $[m_{2MI}^*]_{FW} = [m_{2MI}^*]_{AW}$, $[m_{2M2B}^*]_{FW} = [m_{2M2B}^*]_{AW}$, $[m_{2RI}^*]_{FW} = [m_{2RI}^*]_{AW}$, and $[m_{2R2B}^*]_{FW} = [m_{2R2B}^*]_{AW}$.

In Fig. 4(a) and 4(b), we examine M's and R's profits, respectively. When M's expected value of R's cost is less than its actual cost: $\rho_z > z$, (i) M's profit is more in full information than incomplete information: $[\pi_{2M}^*]_{FW} > [\pi_{2M}^*]_{AW}$, and (ii) R's profit is less in full information than incomplete information: $[\pi_{2MI}^*]_{FW} < [\pi_{2MI}^*]_{AW}$ and $[\pi_{2M2B}^*]_{FW} < [\pi_{2M2B}^*]_{AW}$. We observe that R's profit from the I4I product would be more than the traditional product under both full and incomplete information cases: $[\pi_{2RI}^*]_{FW} > [\pi_{2R2B}^*]_{FW}$ and $[\pi_{2RI}^*]_{AW} > [\pi_{2R2B}^*]_{AW}$. When $\rho_z = z$, M's and R's profits satisfy the following relations: $[\pi_{2M}^*]_{FW} = [\pi_{2M}^*]_{AW}$, $[\pi_{2RI}^*]_{FW} = [\pi_{2RI}^*]_{AW}$, and $[\pi_{2R2B}^*]_{FW} = [\pi_{2R2B}^*]_{AW}$.

From this numerical analysis, we make the following observations: under full and incomplete information cases, (i) M's per unit wholesale price for the I4I product is higher, (ii) both $M's$ and $R's$ unit margins from the I4I product are higher, and (iii) R's profit from the I4I product is higher than the traditional product. Therefore, we understand that it is always beneficial for M and R to incorporate an I4I product line in period $P = 2$.

6. Model extensions

In this section, we extend our analysis by discussing the design of contract preference space and the impact of quantity-dependent innovation cost on M's and R's optimal decisions. The proofs of the theorems are in the appendix and the proofs of the propositions are in the online supplementary material. We present these analyses below.

6.1. Design of contract preference space

From the equilibrium results, we realize that the competition between I4I and traditional product δ, consumer sensitivity to I4I product λ, and Industry 4.0 innovation investment parameter μ impacts the manufacturer M's and retailer R's profits and thus, affects M's and R's contract preference. We design the contract preferred space for M and R under full and incomplete information (refer to Figs. 5–7) using the same parameters as defined in Section 5. The contract space is designed by considering two parameters simultaneously as follows: (δ, λ), (δ, μ), and (μ, λ).

From Fig. 5(a), we understand that a manufacturer offers the L contract for extremely low values of innovation and cross-price sensitivities (refer to zone A). In both full and asymmetric information cases, we observe that a manufacturer offers a W contract only for high values of innovation and cross-price sensitivities (refer to zone B). In case of full information, a manufacturer prefers L contract and a retailer prefers W contract for most of the (δ, λ) space (refer to Fig. 5(a) zone C). However, under asymmetric information, a manufacturer prefers the L contract, and a retailer prefers the W contract when the innovation sensitivity is less and cross-price sensitivity is very high (refer to Fig. 5(b) zone C). Under full and asymmetric information, for extremely high values of innovation and cross-price sensitivities, trade does not happen (refer to Fig. 5 zone F).

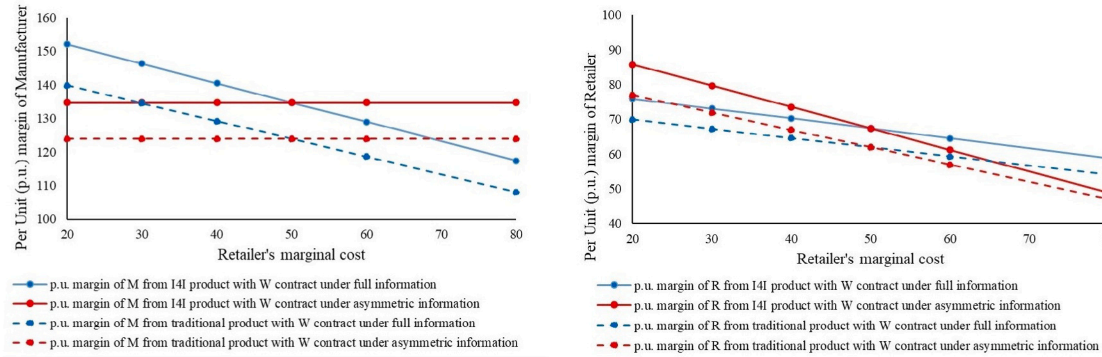
From Fig. 6, we realize that under full and incomplete information cases, a manufacturer prefers the L contract, and a retailer prefers the W contract for high values of innovation investment parameter and cross-price sensitivity (refer to zone C). For low values of the innovation investment parameter, the manufacturer offers the W contract only (refer to Fig. 6 zone B). When the innovation investment parameter is extremely low, trade does not happen under both full and asymmetric information cases (refer to Fig. 6 zone F). Under asymmetric information, a manufacturer prefers the W contract, and a retailer prefers the L contract for extremely high values of innovation investment parameter and extremely low values of competition (refer to Fig. 6(b) zone D).

From Fig. 7, we observe there exists no trading zone for extremely low values of innovation investment parameter under full and incomplete information cases (refer to zone F). With an increase in innovation investment parameters, a manufacturer prefers the L contract under full and incomplete information cases. However, a retailer prefers W contract under full information (refer to Fig. 7(a) zone C) and L contract under asymmetric information (refer to Fig. 7(b) zone E).

From the contract space, we observe that under full information, a manufacturer prefers the L contract, whereas a retailer prefers the W contract for most of the contract space (refer to Figs. 5–7 (a) zone C). However, under asymmetric information, both manufacturer and retailer prefer L contract over W contract for most of the contract space (refer to Figs. 5–7 (b) zone E). When the value of the innovation investment parameter is extremely low, trade does not happen between the manufacturer and the retailer (refer to Figs. 6 and 7 zone F).

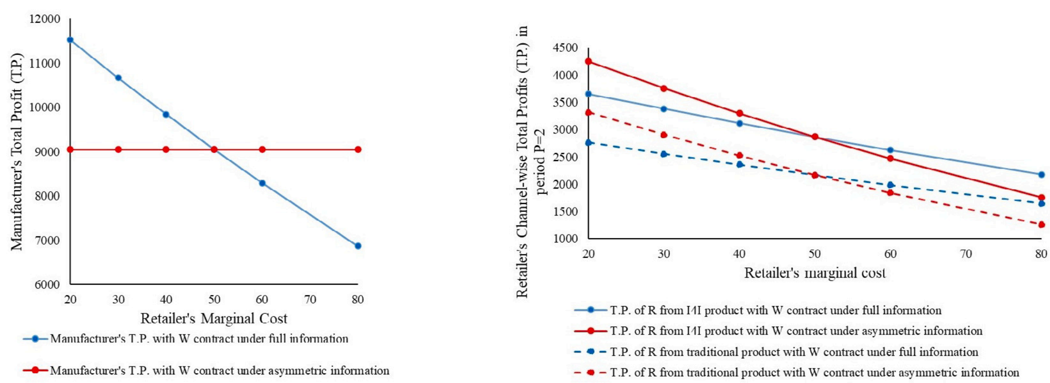
6.2. Impact of quantity dependent innovation cost

In this section, we investigate the impact of a quantity-dependent innovation cost function on the manufacturer M's optimal wholesale



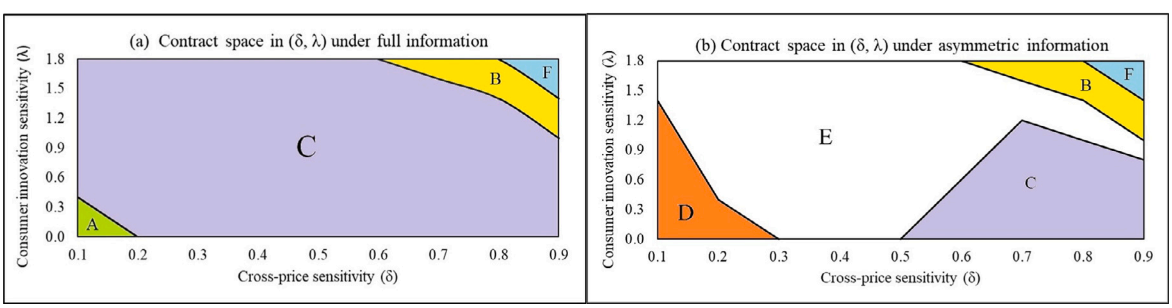
(a) Manufacturer's per unit margin (b) Retailer's per unit margin

Fig. 3. Per unit margins v/s Retailer's marginal cost in W contract.



(a) Manufacturer's total profit (b) Retailer's total profit

Fig. 4. Total profit v/s Retailer's marginal cost in W contract.



Zone A: M can offer only L contract; **Zone B**: M can offer only W contract
Zone C: M prefers L contract and R prefers W contract (Negotiation Zone)
Zone D: M prefers W contract and R prefers L contract (Negotiation Zone)
Zone E: Both M and R prefer L contract; **Zone F**: No trade zone as reservation profit(s) are not met

Fig. 5. Contract matrix in (δ, λ).

contract parameter in period $P = 2$. We consider that M incurs an additional quantity-dependent innovation cost: $H\eta d_I$ apart from $\mu\eta^2$ in period $P = 2$, where $H(\geq 0)$ is the coefficient of quantity-dependent innovation investment, η is the product innovation level, and d_I is the I4I product order quantity. Therefore, the total cost of innovation for M in $P = 2$ is: $\mu\eta^2 + H\eta d_I$. After incorporating this cost function, M's optimization problem of $P = 2$ is updated as follows:

$$(w_{2B}^*, w_I^*, \eta^*) = \max_{w_{2B}, w_I, \eta} \pi_{2M}(w_{2B}, w_I, \eta) = (w_{2B} - y)d_{2B} + \{(w_I - y)d_I - \mu\eta^2 - H\eta d_I\} \quad (8)$$

With all constraints remaining unchanged, we present the solution to this optimization problem in Theorem 6.

Theorem 6. *When manufacturer M's cost of innovation is dependent on both innovation level (η) and quantity (d_I) and she uses W contract in period $P = 2$, then the following statements hold.*

(i) If $H > \frac{2\lambda(1-\delta^2)[8\mu(V_I^2+V_{2B}^2+2\delta V_I V_{2B})-\lambda^2 V_{2B}^2]-2\lambda J_\omega V_{2B}(V_{2B}+\delta V_I)}{[8\mu(V_I^2+V_{2B}^2+2\delta V_I V_{2B})-\lambda^2 V_{2B}^2]-J_\omega(V_{2B}+\delta V_I)^2}$, then M's total profit from selling both I4I and traditional products is higher than her total profit with quantity-independent innovation cost: $[\pi_{2M}^*]_{WQ} - [\pi_{2M}^*]_{FW} > 0$.

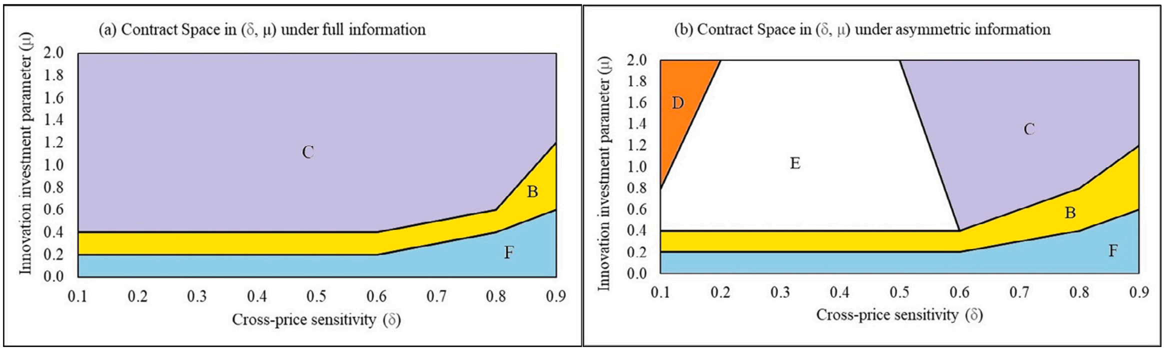


Fig. 6. Contract matrix in (δ, μ). **Note**: Definitions of zones A-F are same as in Fig. 5.

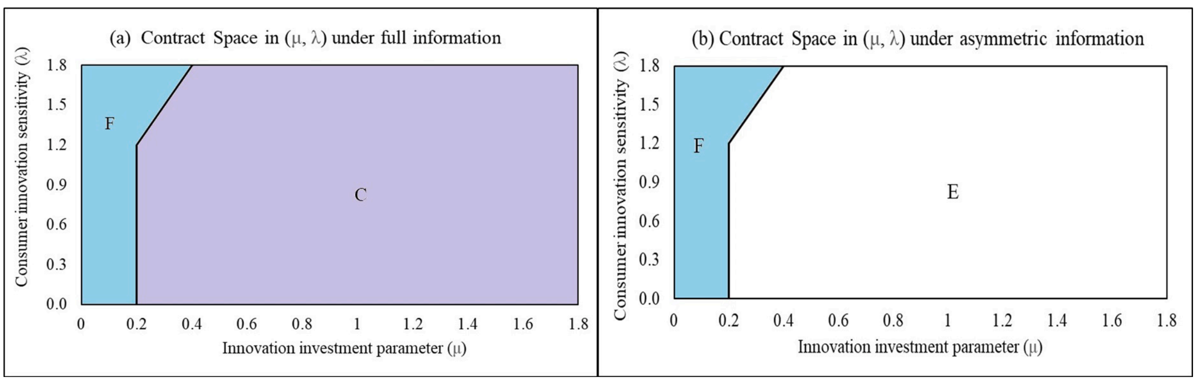


Fig. 7. Contract matrix in (μ, λ). **Note**: Definitions of zones A-F are same as in Fig. 5.

(ii) If $H > \frac{16\lambda\mu(1-\delta^2)(V_I+\delta V_{2B})-J_\omega[\lambda\delta V_{2B}+2(\lambda-\delta)(V_I+\delta V_{2B})]}{8\mu(1-\delta^2)(V_I+\delta V_{2B})+\delta J_\omega(V_{2B}+\delta V_I)}$*, then M's optimal wholesale price of I4I product is higher than that with quantity-independent innovation cost:* $[w_I^*]_{WQ} - [w_I^*]_{FW} > 0$.
(iii) If $H > 2\lambda + \frac{V_I J_\omega}{\lambda(V_I+\delta V_{2B})}$*, then M's optimal product innovation level is higher than that with quantity-independent innovation cost:* $[\eta_I^*]_{WQ} - [\eta_I^*]_{FW} > 0$*, where* $V_i = [\beta\phi_i - (1-\delta)(y+z)]$*,* $i = \{I, 2B\}$*, and* $J_\omega = 8\mu(1-\delta^2) - \lambda^2$.

With quantity dependent innovation cost, M's optimal values in period $P = 2$ are as follows: (i) M's total profit: $[\pi_{2M}^*]_{WQ} = \frac{8\mu(V_I^2+V_{2B}^2+2\delta V_I V_{2B})-\lambda^2 V_{2B}^2-H^2(V_{2B}+\delta V_I)^2+2H\lambda V_{2B}(V_{2B}+\delta V_I)}{8J_{WQ}}$, (ii) M's wholesale price of I4I product: $[w_I^*]_{WQ} = y + \frac{8\mu(V_I+\delta V_{2B})+H[\lambda\delta V_{2B}+2(\lambda-\delta)(V_I+\delta V_{2B})+\delta H(V_{2B}+\delta V_I)]}{2J_{WQ}}$, and (iii) M's optimal product innovation level: $[\eta_I^*]_{WQ} = \frac{\lambda(V_I+\delta V_{2B})-HV_I(1-\delta^2)}{J_{WQ}}$, where $J_{WQ} = 8\mu(1-\delta^2)-\lambda^2+H(1-\delta^2)(2\lambda-H)$. Comparing Theorem 6 and Theorem 2, we observe that when innovation cost is quantity independent: $H = 0$, the following values are the same: $[\pi_{2M}^*]_{WQ} = [\pi_{2M}^*]_{FW}$, $[w_I^*]_{WQ} = [w_I^*]_{FW}$, and $[\eta^*]_{WQ} = [\eta^*]_{FW}$.

Proposition 12. *When manufacturer M introduces I4I production in period* $P = 2$*:*

(i) if $H > \frac{\lambda\{2\lambda^2(1-\delta^2)(V_I+\delta V_{2B})+J_\omega[(V_I+\delta V_{2B})+(1-\delta^2)V_I]\}}{\lambda^2(1-\delta^2)(V_I+\delta V_{2B})+(1-\delta^2)V_I J_\omega}$*, then retailer R orders more of I4I product:* $[d_I^*]_{WQ} - [d_I^*]_{FW} > 0$*;*
(ii) if $H > \frac{48\lambda\mu(1-\delta^2)(V_I+\delta V_{2B})-\lambda J_\omega[4(V_I+\delta V_{2B})+3\delta V_{2B}]}{24\mu(1-\delta^2)(V_I+\delta V_{2B})-(4-\delta)J_\omega(V_I+\delta V_{2B})}$*, then R's optimal retail price of I4I product is also higher:* $[p_I^*]_{WQ} - [p_I^*]_{FW} > 0$*; where* $V_i = [\beta\phi_i - (1-\delta)(y+z)]$*,* $i = \{I, 2B\}$*, and* $J_\omega = 8\mu(1-\delta^2) - \lambda^2$.

From Proposition 12, we understand that the retailer orders more I4I product in the presence of quantity-dependent innovation cost. In this case, we also observe that M's wholesale price is higher with quantity-dependent cost than our base model. This change in wholesale price also affects R's price, and it is presented in the following corollary.

Corollary 3. *When the cost of innovation is dependent on both innovation level (η) and quantity* (d_I)*, retailer R's optimal decisions related to I4I product in period* $P = 2$ *are as follows: (i) the optimal retail price is:* $[p_I^*]_{WQ} = (y+z)+\frac{3}{2}\left[\frac{4\mu(V_I+\delta V_{2B})}{J_{WQ}}\right]+\frac{H[(4\lambda+H\delta-4H)(V_I+\delta V_{2B})+3\delta\lambda V_{2B}]}{4J_{WQ}}$*. (ii) the optimal order quantity is:* $[d_I^*]_{WQ} = \frac{V_I}{4}+\frac{\lambda^2(V_I+\delta V_{2B})}{4J_{WQ}}+\frac{H[HV_I(1-\delta^2)-\lambda(V_I+\delta V_{2B})-\lambda V_I(1-\delta^2)]}{4J_{WQ}}$*, where* $V_i = [\beta\phi_i - (1-\delta)(y+z)]$*,* $i = \{I, 2B\}$*, and* $J_{WQ} = 8\mu(1-\delta^2) - \lambda^2 + H(1-\delta^2)(2\lambda - H)$*.*

From Corollary 3, we see that when innovation cost is quantity independent: $H = 0$, the retailer's pricing strategies given by Proposition 3 and Corollary 3 are the same.

7. Conclusion

In this paper, we examine a manufacturer's strategic choice of incorporating an I4I production line in addition to an existing production line of traditional products. In this context, we have examined a two-period supply chain model wherein the manufacturer is producing only the traditional product in the first period and is planning to add an I4I production channel in the second period. Using game theoretic framework, we examine the retailer's procurement and pricing strategies for both traditional and I4I products under both full and asymmetric information settings using wholesale price and linear two-part tariff contracts. We also analyze the impact of the market potential of the I4I product on the procurement and pricing strategies of the retailer. Further, we extend our model to incorporate the impact of quantity-dependent innovation investment on the manufacturer's total profit and the I4I product innovation level.

Theoretical and Managerial Contributions: From our analysis, we observe that it is advantageous for the manufacturer to add an I4I product line when the manufacturer's total profit after adding an I4I product to the existing traditional product in the second period is higher than the profit from producing just the traditional product. This

Table 2
Research questions, Results, and Managerial Implications.

Research question (s)	Finding (s) from analytical model (s)	Managerial implication (s)
RQ 1: Under what conditions it is advantageous for a traditional product manufacturer to add an I4I production line to her manufacturing processes?	(1) If the manufacturer's total profit after introducing an I4I product line to the existing traditional product line in period $P = 2$ is going to increase M's profit compared to the situation where M does not add an I4I product line in $P = 2$, it is advantageous for M to add an I4I product line, as described in Theorems 2–5. (2) This addition of an I4I product line would be beneficial to the manufacturer if and only if the market potential of I4I product follows a certain range, as described in Propositions 2,4,9.	(1) Manufacturer M should introduce I4I product in the market in the second period ($P = 2$) in order to capture more market when the market potential of I4I product is above a certain range, as discussed in Propositions 2(ii),4(ii),9(ii). (2) Manufacturer M should aggressively market I4I product in the second period ($P = 2$) in order to increase profitability when the market potential of I4I product is beyond a certain range, as discussed in Propositions 2(iii),4(iii),9(iii).
RQ 2: What is the effect of information asymmetry on the manufacturer's innovation level, optimal contract design, the retailer's end-market pricing, and product ordering strategies for I4I and traditional products?	(1) If the manufacturer M chooses channel-wise linear two-part contracts to trade with the retailer R, then M's I4I product innovation level would be higher compared to the channel-wise wholesale price contract case for both full and asymmetric information. (2) If M chooses to trade with R using a wholesale price contract and M's expectation of R's cost exceeds the actual cost, then M's I4I product innovation level will become higher compared to the actual cost case (i.e. the full information case). (3) In both full and asymmetric information cases, R's I4I product order quantity is higher than the traditional product order quantity.	(1) The retailer R would order more I4I products compared to the traditional products despite the higher prices of the I4I product. (2) It is beneficial for the manufacturer to implement channel-wise linear two-part contracts with the retailer in order to coordinate the entire supply chain. (3) When I4I and traditional products have equal market potentials, the retail price of I4I product would be higher than the traditional product for both full and asymmetric information cases. Therefore, it would be beneficial for the retailer to push I4I product in the market.
RQ3: How do contract cessation points (CCPs) and quantity-dependent innovation (QDI) investment impact the manufacturer's profitability and optimal contract design in the presence of both I4I and traditional product lines?	(1) CCPs increase in competition between I4I and traditional products (δ), consumer sensitivity to the I4I product (λ), and decrease in I4I innovation investment parameter (μ). (2) The manufacturer's profit and I4I product innovation level increase in QDI investment, provided conditions mentioned in Theorem 6 are satisfied.	(1) The manufacturer's trading opportunity enhances with increased competition between I4I and traditional products and consumer sensitivity to the I4I product. (2) The retailer orders more I4I products and is able to charge higher retail prices for I4I products when the manufacturer incurs QDI investment cost compared to quantity independent investment cost.

result is supported by what we observe in real life; for instance, Bosch has increased its profitability after expanding to incorporate Industry 4.0 applications. We have derived the exact conditions under which a manufacturer will make a higher profit after introducing an I4I product line and they are reported in Theorem 2–5.

From our comparison of full and asymmetric information game equilibriums, we also demonstrate that the sale of I4I products would be increased compared to traditional products in the case of full information disclosure by the retailer about her cost. Even when the market potentials of both I4I and traditional products are the same, I4I product would be priced higher than the traditional product in the case of full information disclosure. We also demonstrate that information disclosure does not necessarily affect the retailer. With a wholesale price contract, we demonstrate that the manufacturer's I4I product innovation level will be higher if the manufacturer's expectation of the retailer's cost is higher than the retailer's actual cost. From our analysis of the value of information, we understand that a manufacturer's expected profit increases by a certain amount when she has full information about the retailer's per unit cost. This result shows the importance of information disclosure from the manufacturer's perspective while strategizing about adding an I4I product line. This value increases in the consumer sensitivity of I4I products and decreases both in I4I innovation investment and competition.

Our theoretical results support the adoption of the Industry 4.0 standard by Arvind Limited and the adoption of a long-term agreement for this purpose by both ABFRL and Arvind Limited. In our paper, we have modeled long-term agreement using linear two-part tariff contract and have been able to show that such long-term agreements, if properly designed, can coordinate the entire supply chain where the manufacturer simultaneously produces both traditional and I4I products. We observe that the manufacturer's I4I product innovation level will be highest if she is able to implement a channel-wise linear two-part tariff contract. We have summarized our theoretical findings in Table 2.

We observe that the contract cessation points are increasing in competition between I4I and traditional products, consumer sensitivity to the I4I product, and decreasing in Industry 4.0 innovation investment parameter. We observe that when the market potential of the I4I product exceeds a certain threshold, the retailer's order quantity and pricing of the I4I product would be higher than the traditional product. This threshold level decreases in both consumer sensitivity to the I4I product and competition between I4I and traditional products, and increases in innovation investment parameters of Industry 4.0. Even when both innovative and traditional products capture equal market potential, the I4I product's order quantity and retail price would be higher than the traditional product's order quantity and retail price, respectively. We observe that the manufacturer's total profit and innovation level of I4I product increases with quantity-dependent innovation investment.

The main contributions of our paper are as follows: First, we demonstrate that with increasing consumer sensitivity to the I4I product and increasing competition between I4I and traditional products, the critical threshold of the I4I product's market potential decreases. This market potential threshold of the I4I product, if exceeded, results in increased sales of the I4I product compared to the traditional product even when the price of the I4I product is higher in the end market. Second, the sale of the I4I product compared to traditional products is higher in the case of full information compared to asymmetric information. Third, in the channel-wise linear two-art tariff contract, the innovation level of the I4I product chosen by the manufacturer would be higher as compared to the wholesale price contract. Fourth, quantity-dependent innovation investment results in increased manufacturer's profitability and innovation level of the I4I product, provided that the innovation investment coefficient is above a certain threshold.

Future Research Direction: The limitations of our paper include the following. For expositional simplicity, we have assumed demand functions to be deterministic and linear, and supply chain agents to be risk-neutral. However, in reality, demand functions can be stochastic and supply chain agents may be risk-averse. We have not analyzed the impact of these changes in this work, which would be areas for future research.

We have also used a bilateral monopoly framework to examine the impact of I4I product introduction where the manufacturer produces exactly one traditional and one I4I innovative product. In reality, manufacturers handle a family of traditional and I4I innovative products with the demand spill-over effect. Our work can also be extended in that direction. In addition, we have not considered competition among multiple manufacturers (in the upstream) as well as multiple retailers (in the downstream) in our analysis. Finally, we have modeled and analyzed wholesale price and linear two-part tariff contracts. In the future, it would be interesting to explore the cost and revenue-sharing contracts in this context.

Acknowledgments

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Appendix. Proofs

Proof of Theorem 1. In the centralized case, using the Hessian matrix, we understand that $\pi_{2C}(d_I, d_{2B}, \eta)$ is jointly concave in (d_I, d_{2B}, η) when $\delta^2 < 1$, $\mu > \lambda^2/4$, and $\mu > \lambda^2/4(1-\delta^2)$. From the first-order conditions (F.O.C.) of the central planner's profit, we obtain the following: (i) $\partial\pi_{2C}/\partial p_I = 0$, (ii) $\partial\pi_{2C}/\partial p_{2B} = 0$, and (iii) $\partial\pi_{2C}/\partial\eta = 0$. Solving these equations simultaneously, we obtain the values of $[p_I^*]_C$, $[p_{2B}^*]_C$, and $[\eta^*]_C$. Plugging these values in Eq. (2), we get the optimal values of the central planner's profit: $[\pi^*]_{2C} = \frac{\mu(V_I+\delta V_{2B})^2}{J} + \frac{V_{2B}^2}{4}$, where $V_i = \beta\phi_i - (y+z)(1-\delta)$, i=$\{I, 2B\}$ and $J = 4\mu(1-\delta^2) - \lambda^2$. The derivation of critical market potential thresholds is given in Online Supplementary Material.

Proof of Theorem 2. The optimization problem of the FW case in period $P = 2$ is presented by Eqs. (5)–(7). From the F.O.C.s of Eq. (6), we obtain: (i) $\partial\pi_{2R}/\partial m_I = 0$, and (ii) $\partial\pi_{2R}/\partial m_{2B} = 0$, where $m_I = p_I - z - w_I$, $m_{2B} = p_{2B} - z - w_{2B}$, and $\pi_{2R} = \pi_{2RI} + \pi_{2R2B}$. From these F.O.C.s, we obtain: (i) $d_I = [\beta\phi_I - (w_I+z) + \delta(w_{2B}+z) + \lambda\eta]/2$, and (ii) $d_{2B} = [\beta\phi_{2B} - (w_{2B}+z) + \delta(w_I+z)]/2$. Plugging these values in Eq. (5) and from its F.O.C.s, we obtain: (i) $\partial\pi_{2M}/\partial\eta = 0$, (ii) $\partial\pi_{2M}/\partial w_I = 0$, and (iii) $\partial\pi_{2M}/\partial w_{2B} = 0$. From these F.O.Cs, we obtain: (i) $[w_I^*]_{FW}$, (ii) $[w_{2B}^*]_{FW}$, and (iii) $[\eta^*]_{FW}$. Using these values, we obtain the values of $[d_I^*]_{FW}$ and $[d_{2B}^*]_{FW}$. Plugging these values in Eq. (5), we get the optimal values of the manufacturer's profit: $[\pi_{2M}^*]_{FW} = \frac{\mu(V_I+\delta V_{2B})^2}{J_\omega} + \frac{V_{2B}^2}{8}$, where $V_i = [\beta\phi_i - (y+z)(1-\delta)]$, i=$\{I, 2B\}$, and $J_\omega = 8\mu(1-\delta^2) - \lambda^2$.

Proof of Theorem 3. For AW case, we present the Manufacturer's $M's$ optimization problems in periods $P = 1$ and $P = 2$, respectively. M's problem in $P = 1$: $w_{1B}^* = \max_{w_{1B}} E_z(\pi_{1M}(w_{1B})) = \int_{\underline{z}}^{\overline{z}}\{(w_{1B} - y)d_{1B}\}dG(z)$, and M's problem in $P = 2$: $(w_{2B}^*, w_I^*, \eta^*) = \max_{w_{2B}, w_I, \eta} E_z$ $(\pi_{2M}(w_{2B}, w_I, \eta)) = \int_{\underline{z}}^{\overline{z}}\{(w_{2B} - y)d_{2B} + (w_I - y)d_I - \mu\eta^2\}dG(z)$. Under both full and asymmetric information, the F.O.C.s for the retailer's optimization remain the same since the retailer's actual cost is known to her in both cases. From the F.O.C.s of manufacturer's profit, we obtain: (i) $\partial E_z(\pi_{2M})/\partial\eta = 0$, (ii) $\partial E_z(\pi_{2M})/\partial w_I = 0$, and (iii) $\partial E_z(\pi_{2M})/\partial w_{2B} = 0$. From these F.O.C.s, we obtain: (i) $[w_I^*]_{AW}$, (ii) $[w_{2B}^*]_{AW}$, and (iii) $[\eta^*]_{AW}$. Using these values, we obtain the values of $[d_I^*]_{AW}$ and $[d_{2B}^*]_{AW}$. Plugging these values in $E_z(\pi_{2M}(w_{2B}, w_I, \eta))$, we get the optimal values of the manufacturer's profit: $[\pi_{2M}^*]_{AW} = \frac{\mu\{V_I(\rho_z)+\delta V_{2B}(\rho_z)\}^2}{J_\omega} + \frac{V_{2B}^2(\rho_z)}{8}$, where $V_i(\rho_z) = \beta\phi_i - (1-\delta)(y+\rho_z), i = \{I, 2B\}$, $J_\omega = 8\mu(1-\delta^2) - \lambda^2$, and $\rho_z = \int_{\underline{z}}^{\overline{z}} zd\{G(z)\}$.

Proof of Theorem 4. For FL case, the Manufacturer's $M's$ optimization problem in period $P = 2$ is following: $(w_{2B}^*, w_I^*, \eta^*) = \max_{w_{2B}, w_I, \eta} \pi_{2M}(w_{2B}, w_I, \eta) = \{(w_{2B} - y)d_{2B} + T_{2B}\} + \{(w_I - y)d_I - \mu\eta^2 + T_I\}$. The IC_{2R} is as following: $(d_{2B}^*, d_I^*) = \max_{d_{2B}, d_I} \pi_{2R}(d_{2B}, d_I) = \max_{d_{2B}, d_I}\{\pi_{2R2B}(d_{2B}) + \pi_{2RI}(d_I)\}$, where $\pi_{2R2B}(d_{2B}) = (p_{2B} - w_{2B} - z)d_{2B} - T_{2B} \geq \overline{\pi}_{2R2B}$ and $\pi_{2RI}(d_I) = (p_I - w_I - z)d_I T_I \geq \overline{\pi}_{2RI}$. From the F.O.C.s of $\pi_{2R}(d_{2B}, d_I)$, we obtain: (i) $\partial\pi_{2R}/\partial m_I = 0$, and (ii) $\partial\pi_{2R}/\partial m_{2B} = 0$. From these F.O.C.s, we obtain: (i) $d_I = [\beta\phi_I - (w_I+z) + \delta(w_{2B}+z) + \lambda\eta]/2$, and (ii) $d_{2B} = [\beta\phi_{2B} - (w_{2B}+z) + \delta(w_I+z)]/2$. Plugging these values in $\pi_{2RI}(d_I)$ and $\pi_{2R2B}(d_{2B})$, we obtain: (i) $\pi_{2RI} = \pi_{2RI}(w_I, w_{2B}, \eta, T_I)$, and (ii) $\pi_{2R2B} = \pi_{2R2B}(w_I, w_{2B}\ , \eta, T_{2B})$, respectively. The manufacturer's optimal franchise fee is as following: (i) $T_I = \{[\beta\phi_I(1-\delta) - (w_I+z)(1-\delta^2) + \beta\delta + \lambda\eta]/2(1-\delta^2)\}\{[\beta\phi_I - (w_I+z) + (w_{2B}+z)\delta + \lambda\eta]/2\} - \overline{\pi}_{2RI}$, and (ii) $T_{2B} = \{[\beta\phi_{2B}(1-\delta) - (w_{2B}+z)(1-\delta^2) + \beta\delta + \delta\lambda\eta]/2(1-\delta^2)\}\{[\beta\phi_{2B} - (w_{2B}+z) + (w_I+z)\delta]/2\} - \overline{\pi}_{2R2B}$. Using the above values in $\pi_{2M}(w_{2B}, w_I, \eta)$ and from its F.O.C.s, we obtain: (i) $\partial\pi_{2M}/\partial\eta = 0$, (ii) $\partial\pi_{2M}/\partial w_I = 0$, and (iii) $\partial\pi_{2M}/\partial w_{2B} = 0$. From these F.O.C.s, we obtain: (i) $[w_I^*]_{FL}$, (ii) $[w_{2B}^*]_{FL}$, and (iii) $[\eta^*]_{FL}$. Using these values, we obtain the values of $[d_I^*]_{FL}$ and $[d_{2B}^*]_{FL}$. Plugging these values in $\pi_{2M}(w_{2B}, w_I, \eta)$, we get the optimal values of manufacturer's profit: $[\pi_{2M}^*]_{FL} = \frac{\mu(V_I+\delta V_{2B})^2}{J} + \frac{V_{2B}^2}{4} - \overline{\pi}_{2RI} - \overline{\pi}_{2R2B}$, where $V_i = \beta\phi_i - (y+z)(1-\delta)$, i=$\{I, 2B\}$ and $J = 4\mu(1-\delta^2) - \lambda^2$.

Proof of Theorem 5. For AL case, we present the Manufacturer's $M's$ optimization problems in periods $P = 1$ and $P = 2$, respectively. M's problem in $P = 1$: $w_{1B}^* = \max_{w_{1B}} E_z(\pi_{1M}(w_{1B})) = \int_{\underline{z}}^{\overline{z}}\{(w_{1B} - y)d_{1B} + T_{1B}\}dG(z)$ and M's problem in $P = 2$: $(w_{2B}^*, w_I^*, \eta^*) = \max_{w_{2B}, w_I, \eta} E_z$ $(\pi_{2M}(w_{2B}, w_I, \eta)) = \int_{\underline{z}}^{\overline{z}}\{(w_{2B} - y)d_{2B} + T_{2B} + (w_I - y)d_I + T_I - \mu\eta^2\}dG(z)$. Under both full and asymmetric information, the first order conditions for the retailer's optimization remain the same in L contract. Using these equations, we obtain: (i) $\pi_{RI} = \pi_{RI}(w_I, w_{2B}, \eta, T_I)$, and (ii) $\pi_{2R2B} = \pi_{2R2B}(w_I, w_{2B}, \eta, T_{2B})$. In AL case, under optimality, the manufacturer considers the upper limit of the marginal retailer's cost of production $\overline{z}$ while determining the franchise fee so that the retailer gets the minimum reservation profits in the worst case. The manufacturer's optimal franchise fee is as following: (i) $T_I = \{[\beta\phi_I(1-\delta) - (w_I+\overline{z})(1-\delta^2) + \beta\delta + \lambda\eta]/2(1-\delta^2)\}\{[\beta\phi_I - (w_I+\overline{z}) + (w_{2B}+\overline{z})\delta + \lambda\eta]/2\} - \overline{\pi}_{2RI}$, and (ii) $T_{2B} = \{[\beta\phi_{2B}(1-\delta) - (w_{2B}+\overline{z})(1-\delta^2) + \beta\delta + \delta\lambda\eta]/2(1-\delta^2)\}\{[\beta\phi_{2B} - (w_{2B}+\overline{z}) + (w_I+\overline{z})\delta]/2\} - \overline{\pi}_{2R2B}$. Using the above values in $E_z(\pi_{2M}(w_I, w_{2B}, \eta))$ and from its F.O.C.s, we obtain: (i) $\partial E_z(\pi_{2M})/\partial\eta = 0$, (ii) $\partial E_z(\pi_{2M})/\partial w_I = 0$, and (iii) $\partial E_z(\pi_{2M})/\partial w_{2B} = 0$. From these F.O.C.s, we obtain: (i) $[w_I^*]_{AL}$, (ii) $[w_{2B}^*]_{AL}$, and (iii) $[\eta^*]_{AL}$. Using these values, we obtain the values of $[d_I^*]_{AL}$ and $[d_{2B}^*]_{AL}$. Plugging these values in $E_z(\pi_{2M}(w_I, w_{2B}, \eta))$, we get the optimal values of the manufacturer's profit: $[\pi_{2M}^*]_{AL} = \frac{I(V_{I\hat{z}}+\delta V_{2B\hat{z}})^2}{J} + \frac{V_{2B\hat{z}}^2}{8} - \overline{\pi}_{2RI} - \overline{\pi}_{2R2B} + R$, where $V_{i\hat{z}} = V_i(\rho_z) - 2(1-\delta)(\overline{z} - \rho_z)$, $V_{i\overline{z}} = V_i(\rho_z) - (1-\delta)(\overline{z} - \rho_z)$, $i = \{I, 2B\}$, $J_\omega = 8\mu(1-\delta^2) - \lambda^2$, $\rho_z = \int_{\underline{z}}^{\overline{z}} zd\{G(z)\}$, and $R = (\overline{z} - \rho_z)\left[(\lambda^2/4J)\left[(V_{I\hat{z}} + \delta V_{2B\hat{z}}) + (V_{I\overline{z}} + \delta V_{2B\overline{z}})\right] + (V_{I\overline{z}} + V_{2B\overline{z}})/2\right]$.

Proof of Theorem 6. The retailer's optimization equations with quantity-dependent innovation cost are the same as that for wholesale price with quantity-independent innovation cost. Using Eq. (8), we obtain the F.O.C.s of the manufacturer's profit as follows: (i) $\partial\pi_{2M}/\partial\eta = 0$, (ii) $\partial\pi_{2M}/\partial w_I = 0$, and (iii) $\partial\pi_{2M}/\partial w_{2B} = 0$. From these F.O.C.s, we obtain: (i) $[w_I^*]_{WQ}$, (ii) $[w_{2B}^*]_{WQ}$, and (iii) $[\eta^*]_{WQ}$. Using these values, we obtain the values of $[d_I^*]_{WQ}$ and $[d_{2B}^*]_{WQ}$. Plugging these values in Eq. (8), we get the optimal values of the manufacturer's profit: $[\pi_{2M}^*]_{WQ} = \frac{8\mu(V_I^2+V_{2B}^2+2\delta V_I V_{2B}) - \lambda^2 V_{2B}^2 - H^2(V_{2B}+\delta V_I)^2 + 2H\lambda V_{2B}(V_{2B}+\delta V_I)}{8J_{WQ}}$, where $V_i = [\beta\phi_i - (y+z)(1-\delta)]$, $i = \{I, 2B\}$, and $J_{WQ} = 8\mu(1-\delta^2) - \lambda^2 + H(1-\delta^2)(2\lambda - H)$.

Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ejor.2024.01.047.

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