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Research on Supply Chain Digital Collaborative Decision-Making Under Heterogeneous Power Structures

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Abstract

Against the backdrop of the digital economy, digital transformation has increasingly evolved from a firm-level upgrading process into a collaborative decision-making issue among supply chain members. From the perspective of intelligent supply chain management, this study develops a two-echelon game model of a vertical manufacturer–retailer supply chain to examine digital collaborative decision-making under heterogeneous power structures. By comparing a centralized cooperative benchmark with decentralized non-cooperative scenarios, the study investigates how power structures affect firms' digital transformation efforts, pricing decisions, and system-level outcomes, while also considering the role of knowledge spillovers. The results show that, under the same power structure, cooperation leads to higher digital transformation effort levels and greater total supply chain profit than non-cooperation. Knowledge spillovers further strengthen firms' incentives to invest in digital transformation and improve market demand, consumer surplus, and social welfare. Compared with asymmetric power structures, a balanced power structure generates lower retail prices, higher market demand, and better overall supply chain performance. Numerical simulations further show that higher digital transformation costs weaken collaborative gains, whereas greater market sensitivity to digitalization strengthens them. Overall, this study suggests that digital collaboration contributes to supply chain sustainability by improving coordination efficiency, enhancing adaptive operations, and promoting system-level value realization under heterogeneous governance structures.

Keywords: digital transformation; supply chain collaboration; power structure; game model

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1. Introduction

In the context of the accelerating digital economy, digital transformation has become a key path for enterprises to build competitive advantages and achieve high-quality development. Existing research indicates that the embedding of digital technologies not only changes firms' value creation patterns, but also reshapes the fundamental logic of resource allocation, organizational operation, and market competition [1,2]. Furthermore, with the continued diffusion of technologies such as the Internet of Things, big data analytics, artificial intelligence, and cloud computing into supply chains, supply chain management is rapidly moving from a traditional linear operating mode toward a new stage characterized by intelligence, data-driven coordination, and collaboration [3–8]. Digitalization improves information flows and operational activities, enhances supply chain agility, adaptability, and consistency, and thereby promotes efficiency improvement, cost reduction, and value

co-creation [3,4,9]. Therefore, examining digital transformation from the perspective of intelligent supply chain management helps to explain not only how firms improve operational efficiency, but also how digitally connected supply chains sustain coordination, enhance adaptive responses, and improve system-level welfare under interdependent conditions.

However, digital transformation in supply chains cannot be accomplished by a single firm relying solely on its internal resources [10]. In vertical supply chain relationships, digital transformation increasingly depends on interfirm data connectivity, process coordination, and joint decision-making between upstream and downstream firms. For manufacturers and retailers in particular, digital collaboration involves not only technological investment and capability complementarity, but is also embedded in information sharing, benefit distribution, governance arrangements, and power relations [5,11–14]. At the same time, digital activities are typically accompanied by knowledge diffusion and information spillovers. On the one hand, such spillover effects may improve collaborative efficiency and strengthen the expected returns from digital collaboration; on the other hand, they may weaken firms' willingness to cooperate when the benefits from spillovers are unevenly appropriated [15,16]. Thus, supply chain digital collaboration is not merely a matter of firm-level digital upgrading. It also concerns system-level efficiency improvement, flexible responsiveness, and the sustained operation of supply chains.

Supply chain digital collaboration does not occur automatically. Compared with general cooperative settings, supply chain members often differ substantially in digital resource endowment, information processing capability, data application capability, and bargaining position. As a result, collaborative digital transformation is shaped not only by capability allocation but also by power allocation. Under different power structures, differences in pricing authority, resource control, profit distribution, and decision dominance can significantly affect firms' digital investment willingness and their collaborative choices. Existing supply chain research shows that power structures affect key decisions such as product pricing, channel coordination, low-carbon technology adoption, and financing mechanisms [11–14]. Against this background, power structure can reasonably be viewed as an important boundary condition affecting whether supply chain members collaborate, how they collaborate, and how collaborative gains are distributed.

Meanwhile, collaborative digital transformation is often accompanied by knowledge spillovers. The diffusion of digital knowledge, technical experience, and management routines among supply chain partners may reduce transformation costs, improve collaborative efficiency, and enhance overall performance. However, when spillover benefits are unevenly appropriated, firms may become less willing to participate in collaboration. In supply chain contexts, knowledge spillovers do not operate independently of governance conditions; rather, their effects are closely intertwined with power relations among supply chain members. The dominant party may exert greater influence over the distribution of spillover benefits, whereas the weaker party may reduce its collaborative effort when expected returns are insufficient. Therefore, understanding supply chain digital collaborative decision-making requires examining how heterogeneous power structures shape collaboration incentives and how knowledge spillovers affect the returns to such collaboration.

Despite these advances, the existing literature still does not sufficiently explain supply chain digital collaborative decision-making under heterogeneous power structures. Current digital transformation research remains largely focal-firm oriented and therefore says relatively little about how interfirm data connectivity, process integration, and joint decision-making shape digital investment choices in vertical supply chains. At the same time, studies of spillovers have mainly treated them as ex post consequences of digitalization rather than as ex ante expectations entering firms' collaboration logic, while research on power structure has concentrated on conventional operational issues and has paid limited

attention to how governance asymmetry conditions collaborative digital investment and the realization of spillover gains. What remains underdeveloped, therefore, is an integrated explanation of how power differences and spillover expectations jointly shape the formation and consequences of digital collaboration.

Accordingly, this study develops a two-echelon supply chain game model consisting of a manufacturer and a retailer to examine digital collaborative decision-making under heterogeneous power structures. Rather than treating digital transformation as a purely internal upgrading activity, the study conceptualizes it as a collaborative decision problem embedded in vertical supply chain relationships and uses this setting to identify how power differences and knowledge spillovers jointly shape effort choices and system-level outcomes.

On this basis, this study makes three main contributions. First, it repositions digital transformation from a focal-firm phenomenon to an interfirm coordination issue in vertical supply chains, thereby clarifying the collaborative nature of digital investment. Second, instead of examining power structure or knowledge spillovers in isolation, it brings them into the same analytical framework and shows how governance asymmetry conditions the incentive effect of spillover expectations on collaborative digital investment. Third, it evaluates digital collaboration not only from the perspective of firm profit, but also in terms of total supply chain profit, consumer surplus, and social welfare. In this way, it is shown that digital collaboration extends beyond firm-level performance improvement and contributes to system-level efficiency, adaptive operations, and sustainability-related welfare outcomes.

2. Literature Review

2.1. Research on Digital Transformation and Supply Chain Collaboration

With the rapid development of the digital economy, digital transformation has become an important path for enterprises to build competitive advantages and achieve high-quality development [17]. Existing research has mainly examined the implementation pathways, organizational changes, and performance consequences of digital transformation, suggesting that firms can promote digital upgrading through internal process reengineering, external resource integration, and strategic alliances [18]. Related studies further show that digital technologies help manufacturers to reduce costs [19], strengthen information advantages [20–22], and improve production and operational efficiency [22–26]. In supply chain settings, the embedding of digital technologies also improves the matching efficiency of information flows, logistics, and decision flows, thereby enhancing agility, adaptability, and collaborative efficiency and promoting cost reduction and value co-creation [3,4].

As research has progressed, some studies have begun to move beyond the focal-firm perspective and examine digital transformation from a supply chain viewpoint, such as cooperative R&D, data empowerment, and platform connection [5]. This shift suggests that digital transformation is no longer merely an internal upgrading process within a single firm, but increasingly a cross-organizational collaborative process among supply chain members. However, existing studies still tend to emphasize either implementation pathways or performance outcomes, while paying relatively limited attention to the decision logic underlying interfirm digital collaboration. In particular, under vertical supply chain relationships, digital transformation involves not only technological investment and capability complementarity, but also coordination costs, benefit distribution, and governance arrangements. Therefore, the literature still lacks a focused explanation of how supply chain members make collaborative digital transformation decisions and under what conditions such decisions can be sustained.

2.2. Research on Knowledge Spillover in Digital Transformation

Digital transformation is often accompanied by knowledge diffusion, technology transfer, and information sharing, making knowledge spillover an important topic in related research. Existing studies have shown that spillovers are not confined to individual firms or industries, but can also diffuse across industrial linkages, upstream–downstream connections, and cooperative networks [15,16]. In the digital economy, the application and diffusion of digital technologies help firms to improve information processing, optimize resource allocation, and promote productivity enhancement and capability upgrading through knowledge dissemination. From a supply chain perspective, the digital transformation of core firms or focal clients may also affect the operational behaviors and strategic choices of their partners through information spillovers.

This stream of research is important because it reveals the externality characteristics of digital transformation. However, most existing studies still treat knowledge spillovers primarily as outcomes or external impacts of digitalization, rather than as factors entering firms' ex ante decision logic [15,16]. In supply chain collaboration, this distinction is critical. Knowledge spillovers may enhance overall coordination efficiency and strengthen the expected returns from digital collaboration, but they may also weaken cooperation willingness when spillover benefits are unevenly appropriated. Therefore, knowledge spillover should not be understood merely as consequences of digital transformation. They are also important for explaining why firms choose to collaborate and how collaborative digital transformation can be sustained when firms hold asymmetric expectations regarding benefit capture.

2.3. Research on Power Structure and Supply Chain Decision-Making

Power structure is a classic issue in supply chain research. Existing studies generally examine scenarios such as manufacturer dominance, retailer dominance, and symmetric power, and analyze how different power configurations affect firms' pricing, coordination, low-carbon decisions, recycling decisions, and financing arrangements [12]. Related research has shown that power structure influences not only firms' optimal decisions, but also profit distribution, coordination efficiency, and overall supply chain performance [11,14]. As this literature has evolved, scholars have gradually extended the analysis of power structure to more complex supply chain settings in order to reveal how differences in dominance shape firms' behavioral choices [13].

Nevertheless, this stream has remained largely concentrated on conventional operational decisions. Comparatively less attention has been paid to how power heterogeneity affects collaborative decision-making in digital transformation contexts. This omission matters because digital transformation differs from general pricing or channel coordination decisions. It involves not only financial and technological investment, but also data resource control, knowledge absorption, and the allocation of collaborative gains. Under such conditions, power structure is not merely a matter of decision sequencing; it also constitutes an important governance condition that shapes firms' willingness to participate in digital collaboration and their expectations regarding the returns from such collaboration. Accordingly, introducing power structure into supply chain digital collaboration research helps to explain why similar digital opportunities may produce different collaborative choices and system outcomes under different governance arrangements.

2.4. Research Gap

The above literature suggests that digital transformation, knowledge spillovers, and power structure are all closely related to supply chain collaboration. However, these three streams have rarely been integrated into a single analytical logic for explaining digital collaborative decision-making in supply chains.

First, research on digital transformation has generated important insights into implementation paths and performance effects, but it remains largely focal-firm oriented. As a result, it is less able to explain digital transformation in supply chain contexts, where value creation increasingly depends on interfirm data linkage, process coordination, and joint decision-making between upstream and downstream firms. Second, research on knowledge spillovers has clarified the externality characteristics of digitalization, yet it has mainly treated spillovers as ex post consequences of digital transformation. Existing studies have not sufficiently explained how spillover expectations enter firms' ex ante collaboration logic and influence their strategic choices regarding whether and how to engage in digital collaboration. Third, research on supply chain power structure has provided a strong basis for understanding governance asymmetry in conventional operational decisions, but it has not adequately examined how power heterogeneity conditions digital collaboration and the realization of collaborative gains.

3. Problem Description and Model Construction

3.1. Problem Description

This study considers a two-echelon supply chain consisting of a manufacturer (M) and a retailer (R). The manufacturer is responsible for product production and supplies the retailer at a unit wholesale price w; the retailer then sells the product to end consumers. To improve operational efficiency, information processing capabilities, and market responsiveness, both the manufacturer and the retailer can undertake digital transformation and respectively choose their digital transformation effort levels e_M and e_R. On the one hand, digital transformation can directly enhance the enterprise's own operational efficiency; on the other hand, it also generates knowledge spillovers through data sharing, technology diffusion, and experience transfer, thereby impacting the digital benefits of supply chain partners. Meanwhile, the manufacturer and the retailer have differences in resource control, channel status, and bargaining power, which form different power structures. Different power structures not only affect the channel pricing sequence but also further influence the enterprises' digital transformation investments and their collaborative behavioral choices.

This study constructs a two-stage game model. In the first stage, the manufacturer and the retailer make decisions regarding their digital transformation effort levels; in the second stage, both parties make channel pricing decisions based on the established power structure. Depending on whether there is cooperation in the first stage, the decision-making models can be divided into two categories: cooperative and non-cooperative; based on the channel power differences in the second stage, they can be further divided into the Manufacturer-Dominated (MD) model, the Retailer-Dominated (RD) model, and the Balanced Power (BD) model. Accordingly, this study formulates six decision-making scenarios: Manufacturer-dominated Non-cooperative (MN) Model, Retailer-dominated Non-cooperative (RN) model, Balanced power Non-cooperative (BN) model, as well as Manufacturer-dominated Cooperative (MC) model, Retailer-dominated Cooperative (RC) model, and Balanced power Cooperative (BC) model. The game process is illustrated in Figure 1.

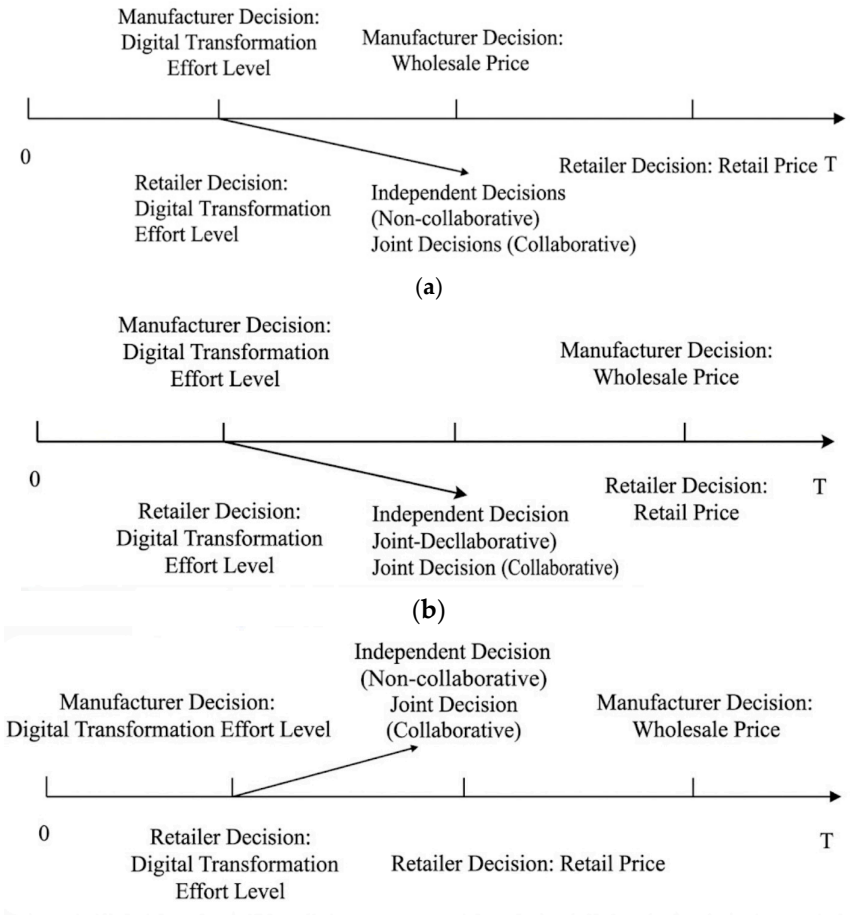


Figure 1. (**a**) Decision sequence under the manufacturer-dominated model; (**b**). Decision sequence under the retailer-dominated model; (**c**) Decision sequence under the balanced power model.

3.2. Assumptions

Assumption 1. *Market demand increases as the retail price decreases and the firms' digitalization levels increase. In this study, the digital transformation of the manufacturer and the retailer is mainly reflected in improvements in information connectivity, process coordination, and responsiveness. These changes enhance supply–demand matching efficiency and service fulfillment capability, thereby exerting a positive effect on market demand. Meanwhile, as the retail price is a direct constraint on consumers' purchasing decisions, a lower retail price leads to higher demand. Following formulations commonly adopted in related supply chain studies [27–29], the market demand function is specified as*:

$$q = a - bp + \alpha(x_M + x_R) \tag{1}$$

where q represents the market demand, a is the potential market demand, b is the sensitivity coefficient of market demand to the retail price, and α is the sensitivity coefficient of the market to the enterprise's digitalization level.

Assumption 2. *To characterize digital knowledge spillovers, the effective digitalization levels of the manufacturer and the retailer are specified as follows:*

$$x_M = e_M + \beta_R e_R, \tag{2}$$

$$x_R = e_R + \beta_M e_M, \tag{3}$$

where $\beta_M \in [0, 1)$ *represents the knowledge spillover coefficient generated by the manufacturer's digital effort towards the retailer, and* $\beta_R \in [0, 1)$ *represents the knowledge spillover coefficient generated by the retailer's digital effort towards the manufacturer. Consequently, substituting Equations (2) and (3) into Equation (1) yields:*

$$q = a - bp + \alpha[(1 + \beta_M)e_M + (1 + \beta_R)e_R] \tag{4}$$

Assumption 3. *Generally, production factors exhibit diminishing marginal productivity. As the manufacturer and the retailer increase their digital transformation effort levels, the marginal cost of digital transformation becomes increasingly higher. To reflect this characteristic, and following related supply chain modeling studies [30,31], this study assumes*:

$$C_M(e_M) = \frac{k_M}{2}e_M^2 \tag{5}$$

$$C_R(e_R) = \frac{k_R}{2}e_R^2 \tag{6}$$

where k_M *and* k_R *represent the digital transformation cost coefficients of the manufacturer and the retailer, respectively.*

Assumption 4. *Under the non-cooperative scenario, the manufacturer and the retailer independently choose* e_M *and* e_R*, with the objective of maximizing their own profits, respectively; under the cooperative scenario, both parties jointly determine them with the objective of maximizing the overall profit of the supply chain.*

Assumption 5. *In the second stage, the retailer's pricing decision is equivalently represented as a unit mark-up decision, denoted as m. Thus, the terminal retail price satisfies:*

$$p = w + m \tag{7}$$

Let the manufacturer's unit production cost be c. Then, the profit functions for the manufacturer and the retailer are respectively given by:

$$\pi_M = (w - c)q - \frac{k_M}{2}e_M^2 \tag{8}$$

$$\pi_R = mq - \frac{k_R}{2}e_R^2 \tag{9}$$

Consequently, the overall profit of the supply chain is:

$$\pi_{SC} = \pi_M + \pi_R = (w + m - c)q - \frac{k_M}{2}e_M^2 - \frac{k_R}{2}e_R^2 \tag{10}$$

Furthermore, consumer surplus and social welfare are respectively represented as:

$$CS = \frac{q^2}{2b} \tag{11}$$

$$SW = \pi_{SC} + CS \tag{12}$$

4. Model Construction and Solution

This study employs backward induction to obtain the equilibrium solutions under the six models. First, given e_M and e_R, we solve for the second-stage channel pricing equilibrium; then, we return to the first stage to solve for the optimal digital transformation

effort levels under cooperative and non-cooperative scenarios. The complete derivations and solution procedures are presented in Appendices A and B.

4.1. Non-Cooperative Model

Under the non-cooperative scenario, the manufacturer and the retailer independently determine their digital transformation effort levels with the objective of maximizing their respective profits.

In the MN model, in the first stage, the manufacturer and the retailer simultaneously determine e_M and e_R, in the second stage, the manufacturer first determines the wholesale price w, and then the retailer determines the unit mark-up m.

Proposition 1. *Under the manufacturer-dominated non-cooperative model, the optimal digital transformation effort levels of the manufacturer and the retailer are* $e_M^{MN*} = \frac{\alpha(1+\beta_M)(a-bc)}{4bk_M\left[1-\frac{\alpha^2(1+\beta_M)^2}{4bk_M}-\frac{\alpha^2(1+\beta_R)^2}{8bk_R}\right]}$ *and* $e_R^{MN*} = \frac{\alpha(1+\beta_R)(a-bc)}{8bk_R\left[1-\frac{\alpha^2(1+\beta_M)^2}{4bk_M}-\frac{\alpha^2(1+\beta_R)^2}{8bk_R}\right]}$*, respectively; the optimal wholesale price, retail price, and market demand are* $w^{MN} = \frac{a+bc+\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{2b}$, $p^{MN} = \frac{3a+bc+3\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{4b}$ *and* $q^{MN} = \frac{a-bc+\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{4}$*, respectively.*

This proposition shows that under the manufacturer-dominated non-cooperative model, the manufacturer has stronger digital investment incentives and thus captures a larger share of the gains from digitalization. This indicates that upstream dominance not only shapes pricing decisions, but also affects how digital transformation incentives are distributed across the supply chain.

In the RN model, in the first stage, the manufacturer and the retailer simultaneously determine e_M and e_R, in the second stage, the retailer first determines the unit mark-up m, and then the manufacturer determines the wholesale price w.

Proposition 2. *Under the retailer-dominated non-cooperative model, the optimal digital transformation effort levels of the manufacturer and the retailer are* $e_M^{RN*} = \frac{\alpha(1+\beta_M)(a-bc)}{8bk_M\left[1-\frac{\alpha^2(1+\beta_M)^2}{8bk_M}-\frac{\alpha^2(1+\beta_R)^2}{4bk_R}\right]}$ *and* $e_R^{RN*} = \frac{\alpha(1+\beta_R)(a-bc)}{4bk_R\left[1-\frac{\alpha^2(1+\beta_M)^2}{8bk_M}-\frac{\alpha^2(1+\beta_R)^2}{4bk_R}\right]}$*, respectively; the optimal wholesale price, retail price, and market demand are* $w^{RN} = \frac{a+3bc+\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{4b}$, $p^{RN} = \frac{3a+bc+3\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{4b}$, *and* $q^{RN} = \frac{a-bc+\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{4}$*, respectively.*

This proposition indicates that under the retailer-dominated non-cooperative mode, digital investment incentives shift toward the retailer. In other words, when channel power moves downstream, the retailer becomes more willing to invest in digital transformation, while the manufacturer's incentive is relatively weakened.

In the BN model, in the first stage, the manufacturer and the retailer simultaneously determine e_M and e_R, in the second stage, both parties simultaneously determine the wholesale price w and the unit mark-up m.

Proposition 3. *Under the balanced power non-cooperative model, the optimal digital transformation effort levels of the manufacturer and the retailer are* $e_M^{BN*} = \frac{2\alpha(1+\beta_M)(a-bc)}{9bk_M\left[1-\frac{2\alpha^2(1+\beta_M)^2}{9bk_M}-\frac{2\alpha^2(1+\beta_R)^2}{9bk_R}\right]}$ *and* $e_R^{BN*} = \frac{2\alpha(1+\beta_R)(a-bc)}{9bk_R\left[1-\frac{2\alpha^2(1+\beta_M)^2}{9bk_M}-\frac{2\alpha^2(1+\beta_R)^2}{9bk_R}\right]}$*, the optimal wholesale price, retail price, and mar-*

ket demand are $w^{BN} = \frac{a+2bc+\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{3b}$, $m^{BN} = \frac{a-bc+\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{3b}$, $p^{BN} = \frac{2a+bc+2\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{3b}$ *and* $q^{BN} = \frac{a-bc+\alpha[(1+\beta_M)e_M+(1+\beta_R)e_R]}{3}$.

This proposition shows that under the balanced-power non-cooperative mode, the manufacturer and the retailer face more symmetric decision conditions, which helps reduce channel distortion. As a result, the retail price is lower and market demand is higher, suggesting that a balanced power structure is more conducive to improving channel efficiency.

4.2. Cooperative Model

Under the cooperative scenario, the manufacturer and the retailer jointly determine their digital transformation effort levels with the objective of maximizing the overall profit of the supply chain. In this study, the cooperative setting is specified as a centralized benchmark to capture the potential coordination gains generated by collaborative digital transformation. It is not intended to describe a coordination mechanism that is automatically achievable in practice, but rather to provide a comparative reference for evaluating how far decentralized decision-making deviates from the ideal coordinated outcome.

In the MC and RC models, although the pricing sequences in the second stage differ, the functional form of the overall operating profit for the supply chain remains identical. Consequently, the optimal digital transformation effort levels for both parties in the first stage are the same. From this perspective, the cooperative mode serves primarily as an analytical benchmark for comparing the effects of different power structures and decision modes, rather than as a direct representation of an already implemented interfirm arrangement.

Proposition 4. *Under the manufacturer-dominated cooperation model and the retailer-dominated cooperation model, the manufacturer's and retailer's optimal digital transformation effort levels are* $e_M^{MC*} = e_M^{RC*} = \frac{3\alpha(1+\beta_M)(a-bc)}{8bk_M\left[1-\frac{3\alpha^2(1+\beta_M)^2}{8bk_M}-\frac{3\alpha^2(1+\beta_R)^2}{8bk_R}\right]}$ *and* $e_R^{MC*} = e_R^{RC*} = \frac{3\alpha(1+\beta_R)(a-bc)}{8bk_R\left[1-\frac{3\alpha^2(1+\beta_M)^2}{8bk_M}-\frac{3\alpha^2(1+\beta_R)^2}{8bk_R}\right]}$, *respectively. Although the profit allocation between the two parties differs in the second stage, the overall supply chain profit remains identical.*

This proposition indicates that, under the cooperative benchmark, the manufacturer and the retailer choose the same digital effort levels in the manufacturer-dominated and retailer-dominated structures. This suggests that once spillover-related externalities are internalized at the supply chain level, the influence of asymmetric power on first-stage digital effort decisions is weakened.

Proposition 5. *Under the balanced-power cooperation model, the manufacturer's and retailer's optimal digital transformation effort levels are* $e_M^{BC*} = \frac{4\alpha(1+\beta_M)(a-bc)}{9bk_M\left[1-\frac{4\alpha^2(1+\beta_M)^2}{9bk_M}-\frac{4\alpha^2(1+\beta_R)^2}{9bk_R}\right]}$ *and* $e_R^{BC*} = \frac{4\alpha(1+\beta_R)(a-bc)}{9bk_R\left[1-\frac{4\alpha^2(1+\beta_M)^2}{9bk_M}-\frac{4\alpha^2(1+\beta_R)^2}{9bk_R}\right]}$, *respectively, while the optimal wholesale price, retail price, and market demand are* $w^{BC} = \frac{a+2bc+\alpha\left[(1+\beta_M)e_M^{BC*}+(1+\beta_R)e_R^{BC*}\right]}{3b}$, $p^{BC} = \frac{2a+bc+2\alpha\left[(1+\beta_M)e_M^{BC*}+(1+\beta_R)e_R^{BC*}\right]}{3b}$ *and* $q^{BC} = \frac{a-bc+\alpha\left[(1+\beta_M)e_M^{BC*}+(1+\beta_R)e_R^{BC*}\right]}{3}$, *respectively.*

This proposition shows that, under the cooperative benchmark, the balanced-power structure combines the benefits of collaborative decision-making and governance balance. It suggests that when spillover-related gains are coordinated more effectively under a balanced structure, the supply chain can achieve stronger digital incentives and better market outcomes.

4.3. Comparative Analysis of Equilibrium Results

Under the above six models, further comparisons yield the following conclusions.

Proposition 6. *Under the same power structure, the digital transformation effort levels of both the manufacturer and the retailer are higher in the cooperation model than in the non-cooperation model, that is,*

$$\begin{gathered} e_M^{MC*} > e_M^{MN*}, e_R^{MC*} > e_R^{MN*} \\ e_M^{RC*} > e_M^{RN*}, e_R^{RC*} > e_R^{RN*} \\ e_M^{BC*} > e_M^{BN*}, e_R^{BC*} > e_R^{BN*} \end{gathered}$$

This proposition shows that, under the same power structure, cooperation helps to internalize the positive externalities of knowledge spillovers and alleviates the under-investment problem under decentralized decision-making, thereby increasing both the manufacturer's and the retailer's digital transformation effort levels.

Proposition 7. *Under the same power structure, the overall supply chain profit in the cooperation model is higher than that in the non-cooperation model, that is,*

$$\pi_{SC}^{MC*} > \pi_{SC}^{MN*}, \pi_{SC}^{RC*} > \pi_{SC}^{RN*}, \pi_{SC}^{BC*} > \pi_{SC}^{BN*}$$

This proposition shows that, under the same power structure, cooperation enables supply chain members to better coordinate their digital transformation decisions and internalize the external benefits generated by knowledge spillovers, thereby improving total supply chain profit.

Proposition 8. *For a given aggregate effective digitalization level* $S = (1+\beta_M)e_M + (1+\beta_R)e_R$*, the manufacturer-dominated and retailer-dominated structures yield the same terminal retail price and market demand, while the balanced-power structure yields a lower terminal retail price and a higher market demand, that is,*

$$\begin{gathered} p^{MN} = p^{RN}, q^{MN} = q^{RN} \\ p^{BN} < p^{MN} = p^{RN}, q^{BN} > q^{MN} = q^{RN} \end{gathered}$$

This proposition shows that, under the same aggregate effective digitalization level, different power structures affect not only profit allocation, but also channel pricing efficiency and market demand realization. In particular, the balanced-power structure is more conducive to lowering retail prices and expanding market demand, thereby improving the market performance of digital collaboration.

Proposition 9. *As the digital knowledge spillover coefficients* β_M *and* β_R *increase, the optimal digital transformation effort levels of both the manufacturer and the retailer increase accordingly, which further enhances market demand, overall supply chain profit, consumer surplus, and social welfare.*

This proposition shows that stronger knowledge spillovers increase both firms' digital effort levels and further improve demand, total profit, consumer surplus, and social welfare. This suggests that knowledge spillovers are not only an outcome of digitalization, but also a key driver of collaborative digital transformation.

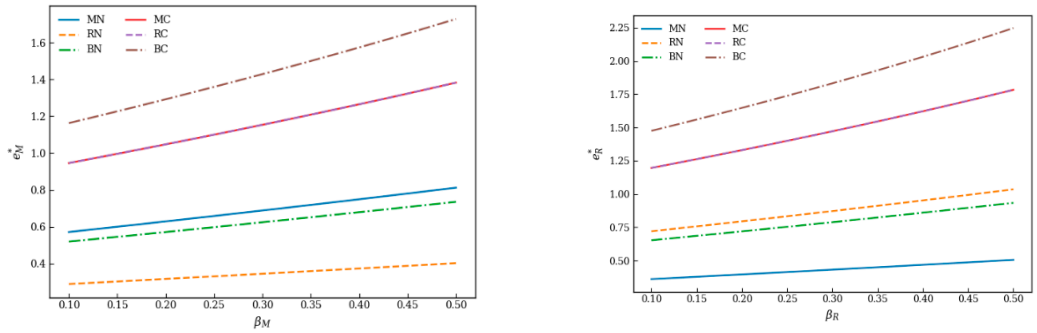
5. Numerical Simulation

To further illustrate the differences in digital collaboration decisions among supply chain members under different power structures and cooperation models, and to verify the

robustness of the preceding analytical results, this study conducts a numerical simulation analysis under a benchmark parameter setting. In accordance with the model specification presented above, the parameters are set as $a = 10$, $b = 1$, $c = 2$, $\alpha = 0.6$, $\beta_M = 0.3$, $\beta_R = 0.2$, $k_M = 2.5$, and $k_R = 2.0$. These values are adopted as benchmark and illustrative settings rather than empirically calibrated estimates, and their main purpose is to provide a unified reference point for comparing equilibrium outcomes across different power structures, cooperation modes, and knowledge spillover conditions. Under this parameter configuration, all models satisfy the conditions for the existence of interior solutions and can therefore be used to compare equilibrium outcomes under different scenarios.

5.1. The Impact of Knowledge Spillovers

Figure 2a illustrates the effect of the manufacturer's knowledge spillover coefficient β_M on the manufacturer's optimal digital transformation effort level. As β_M increases, the manufacturer's optimal digital transformation effort level exhibits a clear upward trend across all six models, indicating that the stronger the system-wide benefits generated through knowledge spillovers from the manufacturer's digital investment, the greater the manufacturer's incentive to invest in digital transformation. A further comparison shows that the manufacturer's effort level under the cooperation models is consistently higher than that under the non-cooperation models, with the BC model yielding the highest level. This suggests that under the combined effects of digital collaboration and balanced power structure, the manufacturer is more inclined to increase its investment in digital transformation.



(**a**) (**b**)

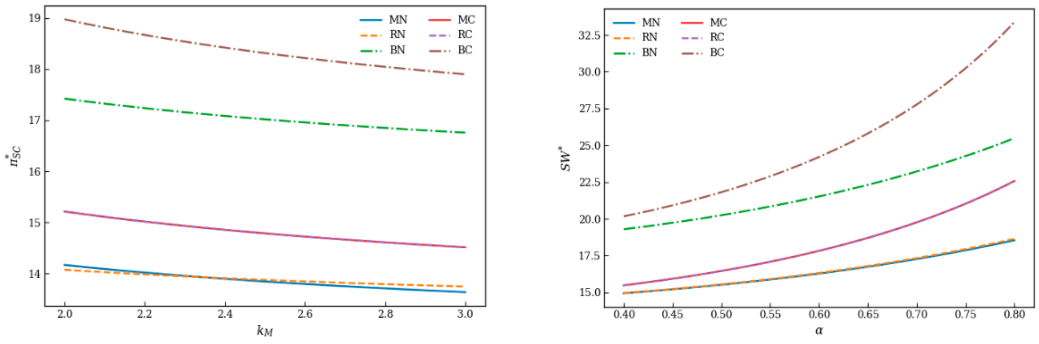
Figure 2. (**a**) Effect of β_M on the manufacturer's digital transformation effort level; (**b**) Effect of β_R on the retailer's digital transformation effort level.

Figure 2b reflects the impact of the retailer's knowledge spillover coefficient β_R on the retailer's optimal digital transformation effort level. As β_R increases, the retailer's optimal digital transformation effort level continues to rise across all models, indicating that the greater the spillover effect generated by the retailer's digital activities, the more it enhances the marginal returns on digital investment, thereby strengthening the retailer's motivation for digital transformation. At the same time, the retailer's effort level under the cooperation models remains consistently higher than that under the non-cooperation models, with the BC model showing the highest level. This further demonstrates a significant positive relationship between knowledge spillovers and collaborative decision-making.

5.2. The Impact of Digital Transformation Costs

Figure 3a illustrates the effect of the manufacturer's digital transformation cost coefficient k_M on the overall supply chain profit. It can be seen that, as k_M increases, the overall supply chain profit declines across all six models, indicating that rising digital transformation costs weaken firms' incentives to invest in digitalization and further reduce

the performance of the supply chain system. A comparison across models shows that the overall supply chain profit is consistently highest under the BC model, followed by the BN model, whereas both the cooperation and non-cooperation models under asymmetric power structures remain relatively lower. This suggests that a more balanced power structure is more conducive to improving overall system returns, while rising costs generally weaken this collaborative advantage.



(**a**) (**b**)

Figure 3. (**a**) Effect of k_M on total supply chain profit; (**b**) Effect of the α on social welfare.

5.3. The Impact of Market Sensitivity to the Level of Digitalization on Social Welfare

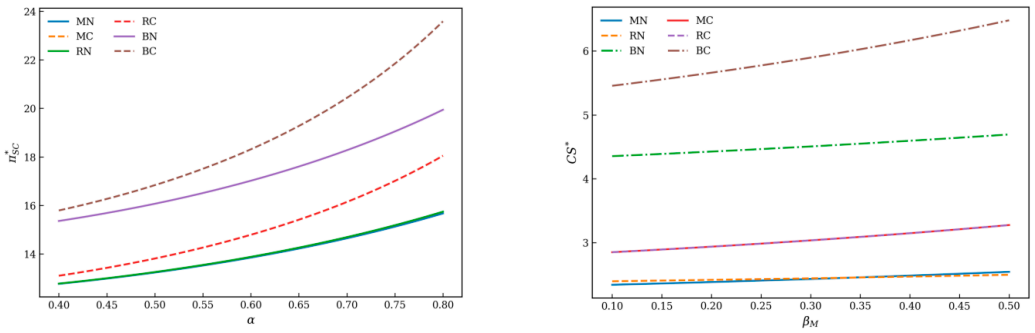
Figure 3b presents the effect of the market sensitivity coefficient to digitalization level, α, on social welfare. As α increases, social welfare rises significantly across all six models, indicating that when consumers and the market place greater value on firms' digitalization level, the demand expansion and welfare improvement effects brought about by digital transformation become more pronounced. A further comparison shows that social welfare is consistently highest under the BC model, followed by the BN model. This suggests that when the market attaches greater importance to digital value, a supply chain structure characterized by more balanced power and a higher degree of collaboration is more conducive to improving overall social welfare.

5.4. Comparison of Different Power Structures and Cooperation Models

Figure 4a further compares the overall supply chain profit under cooperation and non-cooperation models across different power structures as the market sensitivity coefficient to digitalization level, α, changes. It can be observed that, as α increases, the overall supply chain profit rises under all six models, indicating that the more the market values digitalization, the more digital collaboration can generate substantial improvements in system performance. More importantly, under the same power structure, the overall supply chain profit under the cooperation model is consistently higher than that under the non-cooperation model; that is, $MC > MN$, $RC > RN$, and $BC > BN$. This suggests that digital collaboration can effectively internalize the externalities of knowledge spillovers, thereby enhancing the overall profit level of the supply chain. Meanwhile, the BC model consistently remains at the highest level, which further confirms that when power is more balanced, the supply chain is more likely to achieve a high level of collaboration and superior operational performance.

Figure 4b illustrates the effect of the manufacturer's knowledge spillover coefficient β_M on consumer surplus. As β_M increases, consumer surplus shows a clear upward trend across all six models, indicating that the stronger the knowledge spillover generated by the manufacturer's digital activities, the more conducive it is to improving the overall digitalization level of the supply chain, expanding market demand, and further enhancing consumer welfare. A further comparison reveals that consumer surplus is consistently

highest under the BC model, followed by the BN model, while consumer surplus under the manufacturer-dominated and retailer-dominated structures is relatively lower. This suggests that digital collaboration and power balance not only help to improve firm performance, but also contribute more effectively to enhancing consumer welfare through mechanisms such as demand expansion and price adjustment.

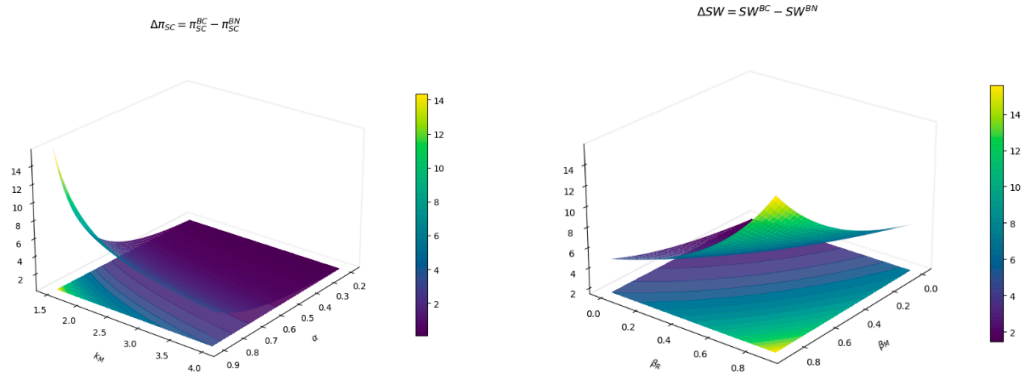


(**a**) (**b**)

Figure 4. (**a**) Comparison of total supply chain profit under cooperation and non-cooperation modes as α changes; (**b**) Effect of β_M on consumer surplus.

5.5. Joint Effect of Market Sensitivity to Digitalization and Transformation Cost on Cooperative Advantage

Figure 5a presents the joint effect of market sensitivity to digitalization and the manufacturer's digital transformation cost on the cooperative advantage in total supply chain profit, measured by $\Delta\pi_{SC} = \pi_{SC}^{BC} - \pi_{SC}^{BN}$. It can be observed that the cooperative advantage increases significantly as the market sensitivity to digitalization rises, while it decreases as the manufacturer's digital transformation cost increases. This indicates that the performance gains generated by digital collaboration are more fully released when the market places greater value on digitalization and when firms face lower transformation costs. By contrast, when market sensitivity is weak and transformation costs are high, the advantage of cooperation over non-cooperation becomes noticeably smaller. Therefore, the figure further shows that the superiority of cooperative digital transformation is not only directionally robust, but also conditional on the joint influence of market demand conditions and cost constraints.



(**a**) (**b**)

Figure 5. (**a**) Joint effect of α and k_M on $\Delta\pi_{SC}$; (**b**) Joint effect of β_M and β_R on ΔSW.

5.6. Joint Effect of Bilateral Knowledge Spillovers on Cooperative Advantage

Figure 5b illustrates the joint effect of the manufacturer's and retailer's knowledge spillover coefficients on the cooperative advantage in social welfare, measured by

$\Delta SW = SW^{BC} - SW^{BN}$. The figure shows that the social welfare advantage of the cooperative mode expands continuously as both spillover coefficients increase. In particular, when the manufacturer and retailer simultaneously exhibit higher spillover levels, the welfare gains from digital collaboration become substantially stronger. This suggests that bilateral knowledge spillovers help to amplify the system-level benefits of digital collaboration, making it easier for collaborative digital transformation to be translated into broader welfare improvement. Hence, the figure further confirms that the performance implications of digital collaboration depend not only on governance structure, but also on the joint strength of interfirm knowledge spillovers.

6. Discussion

This study suggests that digital transformation in supply chains should be understood not as an isolated technology-upgrading decision, but as a collaborative governance issue rooted in interfirm coordination. Existing research has shown that digital technologies such as big data analytics, artificial intelligence, and smart supply chain systems improve information processing, visibility, and responsiveness [3,4,6–8,18]. The present results extend this line of inquiry by showing that the value of digitalization in a manufacturer–retailer relationship depends not only on a firm's own effort, but also on whether the supply chain can coordinate complementary digital investments. In this sense, the cooperation benchmark highlights a structural underinvestment problem in decentralized digital transformation: when spillover-related benefits cannot be fully internalized, firms tend to invest below the system-optimal level.

The results further indicate that power structure is not merely a sequencing condition for pricing decisions; it is also a governance condition that shapes the expectation, allocation, and realization of collaborative gains from digitalization. Existing supply chain research has shown that power asymmetry affects pricing, coordination efficiency, and benefit distribution [11–14]. This study advances that discussion by showing that a more balanced power structure is more likely to translate digital collaboration into lower retail prices, higher market demand, and stronger system-level performance. This implies that the effectiveness of digital collaboration depends on whether the governance structure reduces channel distortion and provides both parties with sufficiently credible expectations of return. From this perspective, knowledge spillovers do not operate as a purely technical externality. Their impact is filtered through the power relationship between firms, because the same spillover opportunity may generate different collaboration incentives under different governance arrangements.

Finally, the numerical simulation results clarify that the gains from digital collaboration are conditional rather than unconditional. Higher digital transformation costs weaken the release of collaborative gains, whereas stronger market sensitivity to digitalization and stronger bilateral spillovers enlarge the performance and welfare advantages of cooperation. This finding is important for sustainability-oriented supply chain research because it suggests that the sustainability value of digital collaboration does not arise automatically from technology adoption itself. Rather, it emerges when digital investment, governance structure, and market response are aligned in a way that supports persistent coordination, reduces channel inefficiency, and translates digital effort into broader system-level welfare improvement. The joint-parameter simulations further reinforce this point by showing that cooperative advantage varies systematically with cost constraints, market valuation of digitalization, and interfirm spillover strength.

7. Conclusions and Management Implications

7.1. Conclusions

Against the backdrop of the deepening digital economy, firms' digital transformation has gradually evolved from internal technological upgrading into a collaborative transformation process among supply chain members. To examine this issue, this study develops a two-echelon supply chain game model consisting of a manufacturer and a retailer, and incorporates cooperative versus non-cooperative decisions under different channel power structures, while further considering the role of knowledge spillovers in collaborative digital transformation. On this basis, it systematically examines the differences in supply chain members' digital collaborative transformation decisions and their economic consequences across different scenarios. This study yields the following main conclusions.

First, digital collaboration helps to enhance supply chain members' digital transformation effort levels and further improves overall system performance. Under the same power structure, both the manufacturer and the retailer invest more in digital transformation under the cooperation model than under the non-cooperation model, and total supply chain profit is also higher. This indicates that digital collaboration can, to some extent, alleviate the underinvestment problem caused by decentralized decision-making and better align individual firms' decisions with overall supply chain gains.

Second, knowledge spillovers constitute an important mechanism driving collaborative digital transformation in the supply chain. As the knowledge spillover coefficients of the manufacturer and retailer increase, the optimal digital transformation effort levels of both parties rise accordingly, and market demand, total supply chain profit, consumer surplus, and social welfare all improve. This suggests that, in digital contexts, information sharing, experience diffusion, and knowledge transfer not only affect the outcomes of digital transformation, but also strengthen firms' incentives to engage in collaborative investment.

Third, channel power structure significantly affects the realization of gains from digital collaboration. Under asymmetric power structures, the differences between manufacturer-dominated and retailer-dominated structures are mainly reflected in profit allocation. In contrast, the balanced-power structure is associated with lower retail prices, higher market demand, and superior outcomes in terms of total supply chain profit, consumer surplus, and social welfare. This indicates that a more balanced governance structure is more effective in alleviating channel inefficiencies and enhancing the systemic benefits of digital collaboration.

Fourth, the effectiveness of digital collaboration is also jointly constrained by cost conditions and market factors. Numerical simulations show that an increase in digital transformation costs weakens total supply chain profit, whereas a higher level of market sensitivity to digitalization strengthens the demand expansion effect and welfare improvement effect generated by digital collaboration. This implies that digital collaboration does not automatically generate superior performance under all circumstances; rather, its effectiveness depends on the investment costs faced by firms and the external market environment.

Taken together, these findings suggest that the sustainability relevance of digital collaboration lies not only in improving economic performance, but also in supporting more coordinated, adaptive, and welfare-enhancing supply chain operation under heterogeneous governance structures.

7.2. Management Implications

Based on the above findings, this study proposes the following managerial implications for vertical dyadic supply chains composed of a manufacturer and a retailer. Because the cooperative setting in this study is specified as a centralized benchmark rather than an implemented contract, the implications below should be understood as governance-

oriented managerial inferences rather than direct prescriptions derived from a specific coordination mechanism.

First, firms should promote digital transformation from the perspective of supply chain collaboration rather than from the perspective of isolated firm-level upgrading. The results suggest that stronger coordination can improve digital transformation effort and overall supply chain performance. Accordingly, firms should place greater emphasis on interfirm data connectivity, process coordination, and collaborative decision-making.

Second, dominant firms should pay closer attention to the governance arrangements through which collaborative gains are shared. Although the model does not endogenize specific contracts, the results imply that digital collaboration is more sustainable when both parties perceive the distribution of gains as credible and acceptable. In practice, firms may move toward this condition through benefit-sharing, cost-sharing, data-sharing arrangements, and collaborative incentives that reduce participation barriers and improve collaboration stability.

Third, comparatively weaker firms should strengthen their absorptive and value realization capabilities. In the model, knowledge spillovers are treated as exogenous parameters; however, the results suggest that firms in weaker positions benefit more from collaboration when they are able to convert available digital knowledge into operational and market gains. For this reason, such firms should improve digital infrastructure, data-processing capability, and organizational learning capacity.

Finally, firms should evaluate digital collaboration jointly in light of transformation costs and market conditions. When market demand is more sensitive to digitalization and transformation costs remain manageable, collaborative investment is more likely to generate a meaningful performance premium. Firms should therefore prioritize digital initiatives that more directly improve coordination efficiency, responsiveness, and demand realization.

8. Theoretical Implications and Future Study

8.1. Theoretical Implications

This study offers three main theoretical implications.

First, the study advances digital transformation research by repositioning digitalization from a focal-firm upgrading issue to an interfirm coordination problem in vertical supply chains. Prior research has mainly examined digital transformation in terms of organizational change, capability development, and performance improvement within individual firms [1,2,17,18]. By contrast, this study shows that, in supply chain settings, the value of digital transformation depends not only on a firm's own investment effort but also on whether upstream and downstream partners can coordinate complementary digital actions under conditions of interdependence. In this sense, the study extends digital transformation research from firm-level adaptation to collaborative decision-making across organizational boundaries and clarifies the governance character of digital investment in vertical supply chains.

Second, this study contributes to research on supply chain digital collaboration by showing that the effects of knowledge spillovers are contingent on governance structure rather than independent of it. Existing studies have examined power structures mainly in relation to pricing, coordination efficiency, and profit allocation [11–14], while research on spillovers has more often emphasized their externality attributes and performance consequences [15,16]. By incorporating heterogeneous power structures and knowledge spillovers into the same analytical framework, this study shows that collaborative digital investment is shaped by the joint influence of spillover expectations and governance asymmetry. This means that digital collaboration should be understood not merely as a technology investment issue, but also as a governance problem concerning how expected

gains are coordinated, distributed, and realized. From this perspective, the study contributes to intelligent supply chain management research by identifying the governance conditions under which digital collaboration is more likely to be translated into channel outcomes and system-level performance.

Third, this study broadens the analytical relevance of supply chain digital collaboration by extending performance evaluation from firm-level outcomes to system-level consequences and by clarifying the sustainability significance of digital coordination in vertical supply chains. Existing studies have mainly assessed digital transformation in terms of firm profit, operational efficiency, or coordination performance. In contrast, this study further incorporates total supply chain profit, consumer surplus, and social welfare, thereby providing a more comprehensive account of the broader consequences of collaborative digital transformation. More importantly, the study suggests that the sustainability relevance of digital collaboration should be understood in terms of its capacity to sustain interfirm coordination, reduce channel inefficiency, enhance adaptive supply chain operation, and improve welfare outcomes at the system level. In this sense, the study connects digital collaboration research more explicitly to sustainability-oriented discussions of how supply chains remain efficient, responsive, and viable under heterogeneous governance conditions.

8.2. Limitations and Future Research

Although this study provides a parsimonious analytical framework for understanding digital collaboration in supply chains, several limitations remain.

First, the model is restricted to a dyadic manufacturer–retailer setting. This may limits the generalizability of the findings to more complex supply networks involving multiple actors, platforms, and broader digital ecosystems. Future research could extend the analysis to multi-echelon, multi-actor, and platform-based contexts.

Second, knowledge spillovers are treated as exogenous, and the cooperative setting is modeled as a centralized benchmark. While these assumptions help to isolate the logic of digital collaboration, they do not fully capture how spillovers are formed or how collaborative outcomes are implemented through specific coordination mechanisms, such as data sharing, cost sharing, benefit sharing, transfer payments, or other incentive compatible arrangements. Future research could address these issues by endogenizing spillovers and incorporating more explicit coordination designs.

Third, the model implicitly assumes a relatively symmetric information environment between the manufacturer and the retailer, and adopts several stylized functional forms, such as linear demand and quadratic costs, to preserve analytical tractability. In real digital supply chains, however, information asymmetry, platform information advantages, nonlinear demand responses, and more complex cost structures may all affect collaborative decision-making. Future research could relax these assumptions to provide a richer understanding of digital collaboration under more realistic conditions.

Finally, this study adopts a static theoretical modeling approach and has not yet been empirically validated. The numerical simulations are based on benchmark and illustrative parameter settings rather than empirically calibrated estimates. Future research could combine dynamic modeling with empirical testing based on case evidence, survey data, or firm-level calibration to improve the robustness, external validity, and practical relevance of the findings.

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Appendix A

Appendix A.1. Proof of Proposition 1–5

To simplify notation, let $S = (1+\beta_M)e_M + (1+\beta_R)e_R$, so that the demand function in Equation (4) can be rewritten as $q = a - bp + \alpha S$. Since $p = w + m$, the demand function can also be written as $q = a - b(w+m) + \alpha S$. The detailed derivations under the five decision Models are presented below.

Appendix A.1.1. MN Model

Under the MN Model, the manufacturer and the retailer first determine e_M and e_R simultaneously. In the second stage, the manufacturer first chooses the wholesale price w, and the retailer then determines the unit mark-up m. The profit functions are $\pi_M^{MN} = (w-c)[a - b(w+m) + \alpha S] - \frac{k_M}{2}e_M^2$, $\pi_R^{MN} = m[a - b(w+m) + \alpha S] - \frac{k_R}{2}e_R^2$.

We solve the game by backward induction.

In the second stage, given w, e_M, and e_R, the retailer solves $\max_m \pi_R^{MN} = m[a - b(w+m) + \alpha S] - \frac{k_R}{2}e_R^2$. The first-order condition with respect to m is $\frac{\partial \pi_R^{MN}}{\partial m} = a - b(w+m) + \alpha S - bm = a - bw - 2bm + \alpha S = 0$.

Hence, the retailer's optimal response is

$$m^{MN} = \frac{a - bw + \alpha S}{2b} \tag{A1}$$

Substituting Equation (A1) into the demand function gives

$$q = a - b\left(w + \frac{a - bw + \alpha S}{2b}\right) + \alpha S = \frac{a - bw + \alpha S}{2} \tag{A2}$$

Then the manufacturer's problem becomes $\max_w \pi_M^{MN} = (w-c)\frac{a-bw+\alpha S}{2} - \frac{k_M}{2}e_M^2$. The first-order condition with respect to w is $\frac{\partial \pi_M^{MN}}{\partial w} = \frac{a-bw+\alpha S}{2} - \frac{b(w-c)}{2} = 0$, which yields $a + bc + \alpha S - 2bw = 0$.

Therefore,

$$w^{MN} = \frac{a + bc + \alpha S}{2b} \tag{A3}$$

Substituting Equation (A3) into Equation (A1), we obtain

$$m^{MN} = \frac{a - bc + \alpha S}{4b} \tag{A4}$$

Thus, the retail price and market demand are

$$p^{MN} = w^{MN} + m^{MN} = \frac{3a + bc + 3\alpha S}{4b} \tag{A5}$$

$$q^{MN} = \frac{a - bc + \alpha S}{4} \tag{A6}$$

Substituting the above results into the profit functions gives

$$\pi_M^{MN} = \frac{(a - bc + \alpha S)^2}{8b} - \frac{k_M}{2} e_M^2 \tag{A7}$$

$$\pi_R^{MN} = \frac{(a - bc + \alpha S)^2}{16b} - \frac{k_R}{2} e_R^2 \tag{A8}$$

In the first stage, the manufacturer and the retailer choose e_M and e_R simultaneously. The first-order conditions are

$$\frac{\partial \pi_M^{MN}}{\partial e_M} = \frac{\alpha(1 + \beta_M)(a - bc + \alpha S)}{4b} - k_M e_M = 0 \tag{A9}$$

$$\frac{\partial \pi_R^{MN}}{\partial e_R} = \frac{\alpha(1 + \beta_R)(a - bc + \alpha S)}{8b} - k_R e_R = 0 \tag{A10}$$

From Equations (A9) and (A10), we have

$$e_M = \frac{\alpha(1 + \beta_M)(a - bc + \alpha S)}{4bk_M} \tag{A11}$$

$$e_R = \frac{\alpha(1 + \beta_R)(a - bc + \alpha S)}{8bk_R} \tag{A12}$$

Substituting Equations (A11) and (A12) into $S = (1 + \beta_M)e_M + (1 + \beta_R)e_R$, we obtain

$$S = \frac{\alpha(1 + \beta_M)^2(a - bc + \alpha S)}{4bk_M} + \frac{\alpha(1 + \beta_R)^2(a - bc + \alpha S)}{8bk_R} \tag{A13}$$

Equivalently,

$$a - bc + \alpha S = \frac{a - bc}{1 - \frac{\alpha^2(1+\beta_M)^2}{4bk_M} - \frac{\alpha^2(1+\beta_R)^2}{8bk_R}} \tag{A14}$$

Substituting Equation (A14) back into Equations (A11) and (A12) yields

$$e_M^{MN*} = \frac{\alpha(1 + \beta_M)(a - bc)}{4bk_M\left[1 - \frac{\alpha^2(1+\beta_M)^2}{4bk_M} - \frac{\alpha^2(1+\beta_R)^2}{8bk_R}\right]} \tag{A15}$$

$$e_R^{MN*} = \frac{\alpha(1 + \beta_R)(a - bc)}{8bk_R\left[1 - \frac{\alpha^2(1+\beta_M)^2}{4bk_M} - \frac{\alpha^2(1+\beta_R)^2}{8bk_R}\right]} \tag{A16}$$

Appendix A.1.2. RN Model

Under the RN Model, the manufacturer and the retailer first determine e_M and e_R simultaneously. In the second stage, the retailer first chooses the unit mark-up m, and the manufacturer then determines the wholesale price w. The profit functions are $\pi_M^{RN} = (w - c)[a - b(w + m) + \alpha S] - \frac{k_M}{2} e_M^2$, $\pi_R^{RN} = m[a - b(w + m) + \alpha S] - \frac{k_R}{2} e_R^2$.

Given m, e_M, and e_R, the manufacturer solves $\max_w \pi_M^{RN}$. The first-order condition with respect to w is $\frac{\partial \pi_M^{RN}}{\partial w} = a - b(w + m) + \alpha S - b(w - c) = 0$, which gives $a + bc - bm + \alpha S - 2bw = 0$.

Hence,

$$w = \frac{a + bc - bm + \alpha S}{2b} \tag{A17}$$

Substituting Equation (A17) into the demand function yields

$$q = a - b\left(\frac{a + bc - bm + \alpha S}{2b} + m\right) + \alpha S = \frac{a - bc - bm + \alpha S}{2} \tag{A18}$$

Then the retailer's problem becomes $\max_m \pi_R^{RN} = m \cdot \frac{a-bc-bm+\alpha S}{2} - \frac{k_R}{2} e_R^2$. The first-order condition with respect to m is $\frac{\partial \pi_R^{RN}}{\partial m} = \frac{a-bc-bm+\alpha S}{2} - \frac{bm}{2} = \frac{a-bc-2bm+\alpha S}{2} = 0$, which implies

$$m^{RN} = \frac{a - bc + \alpha S}{2b} \tag{A19}$$

Substituting Equation (A19) into Equation (A17), we obtain

$$w^{RN} = \frac{a + 3bc + \alpha S}{4b} \tag{A20}$$

Thus, the retail price and market demand are

$$p^{RN} = w^{RN} + m^{RN} = \frac{3a + bc + 3\alpha S}{4b} \tag{A21}$$

$$q^{RN} = \frac{a - bc + \alpha S}{4} \tag{A22}$$

Substituting these expressions into the profit functions yields

$$\pi_M^{RN} = \frac{(a - bc + \alpha S)^2}{16b} - \frac{k_M}{2} e_M^2 \tag{A23}$$

$$\pi_R^{RN} = \frac{(a - bc + \alpha S)^2}{8b} - \frac{k_R}{2} e_R^2 \tag{A24}$$

The first-stage first-order conditions are

$$\frac{\partial \pi_M^{RN}}{\partial e_M} = \frac{\alpha(1 + \beta_M)(a - bc + \alpha S)}{8b} - k_M e_M = 0 \tag{A25}$$

$$\frac{\partial \pi_R^{RN}}{\partial e_R} = \frac{\alpha(1 + \beta_R)(a - bc + \alpha S)}{4b} - k_R e_R = 0 \tag{A26}$$

Hence,

$$e_M = \frac{\alpha(1 + \beta_M)(a - bc + \alpha S)}{8bk_M} \tag{A27}$$

$$e_R = \frac{\alpha(1 + \beta_R)(a - bc + \alpha S)}{4bk_R} \tag{A28}$$

Substituting these into $S = (1 + \beta_M)e_M + (1 + \beta_R)e_R$, we obtain

$$S = \frac{\alpha(1 + \beta_M)^2(a - bc + \alpha S)}{8bk_M} + \frac{\alpha(1 + \beta_R)^2(a - bc + \alpha S)}{4bk_R} \tag{A29}$$

Therefore,

$$a - bc + \alpha S = \frac{a - bc}{1 - \frac{\alpha^2(1+\beta_M)^2}{8bk_M} - \frac{\alpha^2(1+\beta_R)^2}{4bk_R}} \tag{A30}$$

Substituting Equation (A30) into Equations (A27) and (A28), we obtain

$$e_M^{RN*} = \frac{\alpha(1+\beta_M)(a-bc)}{8bk_M\left[1 - \frac{\alpha^2(1+\beta_M)^2}{8bk_M} - \frac{\alpha^2(1+\beta_R)^2}{4bk_R}\right]} \tag{A31}$$

$$e_R^{RN*} = \frac{\alpha(1+\beta_R)(a-bc)}{4bk_R\left[1-\frac{\alpha^2(1+\beta_M)^2}{8bk_M}-\frac{\alpha^2(1+\beta_R)^2}{4bk_R}\right]} \tag{A32}$$

Appendix A.1.3. BN Model

Under the BN Model, the manufacturer and the retailer first determine e_M and e_R simultaneously. In the second stage, the manufacturer and the retailer choose w and m simultaneously. Their profit functions are $\pi_M^{BN} = (w-c)[a-b(w+m)+\alpha S] - \frac{k_M}{2}e_M^2$, $\pi_R^{BN} = m[a-b(w+m)+\alpha S] - \frac{k_R}{2}e_R^2$.

In the second stage, the manufacturer solves $\max_w \pi_M^{BN}$, and the retailer solves $\max_m \pi_R^{BN}$. The first-order conditions are

$$\frac{\partial \pi_M^{BN}}{\partial w} = a - b(w+m) + \alpha S - b(w-c) = 0 \tag{A33}$$

$$\frac{\partial \pi_R^{BN}}{\partial m} = a - b(w+m) + \alpha S - bm = 0 \tag{A34}$$

Equivalently,

$$2bw + bm = a + bc + \alpha S \tag{A35}$$

$$bw + 2bm = a + \alpha S \tag{A36}$$

Solving Equations (A35) and (A36) simultaneously gives

$$w^{BN} = \frac{a+2bc+\alpha S}{3b} \tag{A37}$$

$$m^{BN} = \frac{a-bc+\alpha S}{3b} \tag{A38}$$

Thus, the retail price and market demand are

$$p^{BN} = w^{BN} + m^{BN} = \frac{2a+bc+2\alpha S}{3b} \tag{A39}$$

$$q^{BN} = a - b\left(w^{BN}+m^{BN}\right) + \alpha S = \frac{a-bc+\alpha S}{3} \tag{A40}$$

Substituting these into the profit functions yields

$$\pi_M^{BN} = \frac{(a-bc+\alpha S)^2}{9b} - \frac{k_M}{2}e_M^2 \tag{A41}$$

$$\pi_R^{BN} = \frac{(a-bc+\alpha S)^2}{9b} - \frac{k_R}{2}e_R^2 \tag{A42}$$

The first-order conditions with respect to e_M and e_R are

$$\frac{\partial \pi_M^{BN}}{\partial e_M} = \frac{2\alpha(1+\beta_M)(a-bc+\alpha S)}{9b} - k_M e_M = 0 \tag{A43}$$

$$\frac{\partial \pi_R^{BN}}{\partial e_R} = \frac{2\alpha(1+\beta_R)(a-bc+\alpha S)}{9b} - k_R e_R = 0 \tag{A44}$$

Hence,

$$e_M = \frac{2\alpha(1+\beta_M)(a-bc+\alpha S)}{9bk_M} \tag{A45}$$

$$e_R = \frac{2\alpha(1+\beta_R)(a-bc+\alpha S)}{9bk_R} \tag{A46}$$

Substituting Equations (A45) and (A46) into S, we obtain

$$S = \frac{2\alpha(1+\beta_M)^2(a-bc+\alpha S)}{9bk_M} + \frac{2\alpha(1+\beta_R)^2(a-bc+\alpha S)}{9bk_R} \tag{A47}$$

Therefore,

$$a - bc + \alpha S = \frac{a-bc}{1 - \frac{2\alpha^2(1+\beta_M)^2}{9bk_M} - \frac{2\alpha^2(1+\beta_R)^2}{9bk_R}} \tag{A48}$$

Substituting Equation (A48) into Equations (A45) and (A46), we have

$$e_M^{BN*} = \frac{2\alpha(1+\beta_M)(a-bc)}{9bk_M\left[1 - \frac{2\alpha^2(1+\beta_M)^2}{9bk_M} - \frac{2\alpha^2(1+\beta_R)^2}{9bk_R}\right]} \tag{A49}$$

$$e_R^{BN*} = \frac{2\alpha(1+\beta_R)(a-bc)}{9bk_R\left[1 - \frac{2\alpha^2(1+\beta_M)^2}{9bk_M} - \frac{2\alpha^2(1+\beta_R)^2}{9bk_R}\right]} \tag{A50}$$

Appendix A.1.4. MC Model and RC Model

Under the cooperative scenario, the manufacturer and the retailer jointly determine e_M and e_R with the objective of maximizing total supply chain profit. In this study, the cooperative model is treated as a centralized benchmark used to identify the potential coordination gains from collaborative digital transformation. For the MC and RC Models, although the pricing sequence differs in the second stage, the total operating profit function of the supply chain takes the same form.

The market demand under the manufacturer-dominated and retailer-dominated structures is identical:

$$q = \frac{a-bc+\alpha S}{4} \tag{A51}$$

Under both structures, the supply chain's operating margin is $p - c = \frac{3(a-bc+\alpha S)}{4b}$. Therefore, the total profit of the supply chain is

$$\pi_{SC}^{MC} = \pi_{SC}^{RC} = \frac{3(a-bc+\alpha S)^2}{16b} - \frac{k_M}{2}e_M^2 - \frac{k_R}{2}e_R^2 \tag{A52}$$

The first-order conditions are

$$\frac{\partial \pi_{SC}^{MC}}{\partial e_M} = \frac{3\alpha(1+\beta_M)(a-bc+\alpha S)}{8b} - k_M e_M = 0 \tag{A53}$$

$$\frac{\partial \pi_{SC}^{MC}}{\partial e_R} = \frac{3\alpha(1+\beta_R)(a-bc+\alpha S)}{8b} - k_R e_R = 0 \tag{A54}$$

Hence,

$$e_M = \frac{3\alpha(1+\beta_M)(a-bc+\alpha S)}{8bk_M} \tag{A55}$$

$$e_R = \frac{3\alpha(1+\beta_R)(a-bc+\alpha S)}{8bk_R} \tag{A56}$$

Substituting these into S, we obtain

$$S = \frac{3\alpha(1+\beta_M)^2(a-bc+\alpha S)}{8bk_M} + \frac{3\alpha(1+\beta_R)^2(a-bc+\alpha S)}{8bk_R} \tag{A57}$$

Therefore,

$$a - bc + \alpha S = \frac{a - bc}{1 - \frac{3\alpha^2(1+\beta_M)^2}{8bk_M} - \frac{3\alpha^2(1+\beta_R)^2}{8bk_R}} \tag{A58}$$

Substituting Equation (A58) into Equations (A55) and (A56), we obtain

$$e_M^{MC*} = e_M^{RC*} = \frac{3\alpha(1+\beta_M)(a-bc)}{8bk_M\left[1 - \frac{3\alpha^2(1+\beta_M)^2}{8bk_M} - \frac{3\alpha^2(1+\beta_R)^2}{8bk_R}\right]} \tag{A59}$$

$$e_R^{MC*} = e_R^{RC*} = \frac{3\alpha(1+\beta_R)(a-bc)}{8bk_R\left[1 - \frac{3\alpha^2(1+\beta_M)^2}{8bk_M} - \frac{3\alpha^2(1+\beta_R)^2}{8bk_R}\right]} \tag{A60}$$

Once the optimal effort levels are obtained, the equilibrium prices, demand, and profits in the MC and RC Models are derived by substituting e_M^{MC*}, e_R^{MC*}, e_M^{RC*}, and e_R^{RC*} into the second-stage pricing expressions under the manufacturer-dominated and retailer-dominated structures, respectively. In particular, $w^{MC} = \frac{a+bc+\alpha\left[(1+\beta_M)e_M^{MC*}+(1+\beta_R)e_R^{MC*}\right]}{2b}$, $p^{MC} = \frac{3a+bc+3\alpha\left[(1+\beta_M)e_M^{MC*}+(1+\beta_R)e_R^{MC*}\right]}{4b}$, $q^{MC} = \frac{a-bc+\alpha\left[(1+\beta_M)e_M^{MC*}+(1+\beta_R)e_R^{MC*}\right]}{4}$, while $w^{RC} = \frac{a+3bc+\alpha\left[(1+\beta_M)e_M^{RC*}+(1+\beta_R)e_R^{RC*}\right]}{4b}$, $p^{RC} = \frac{3a+bc+3\alpha\left[(1+\beta_M)e_M^{RC*}+(1+\beta_R)e_R^{RC*}\right]}{4b}$, $q^{RC} = \frac{a-bc+\alpha\left[(1+\beta_M)e_M^{RC*}+(1+\beta_R)e_R^{RC*}\right]}{4}$.

Thus, although the profit allocation differs across MC and RC because of the different second-stage pricing sequence, the total supply chain profit is identical.

Appendix A.1.5. BC Model

Under the BC Model, the manufacturer and the retailer jointly determine e_M and e_R in the first stage, while in the second stage they choose w and m simultaneously. From the second-stage simultaneous-move pricing structure, the demand function is

$$q = \frac{a - bc + \alpha S}{3} \tag{A61}$$

Since $p - c = \frac{2(a-bc+\alpha S)}{3b}$, the total supply chain profit is

$$\pi_{SC}^{BC} = \frac{2(a - bc + \alpha S)^2}{9b} - \frac{k_M}{2}e_M^2 - \frac{k_R}{2}e_R^2 \tag{A62}$$

The first-order conditions are

$$\frac{\partial \pi_{SC}^{BC}}{\partial e_M} = \frac{4\alpha(1+\beta_M)(a-bc+\alpha S)}{9b} - k_M e_M = 0 \tag{A63}$$

$$\frac{\partial \pi_{SC}^{BC}}{\partial e_R} = \frac{4\alpha(1+\beta_R)(a-bc+\alpha S)}{9b} - k_R e_R = 0 \tag{A64}$$

Thus,

$$e_M = \frac{4\alpha(1+\beta_M)(a-bc+\alpha S)}{9bk_M} \tag{A65}$$

$$e_M = \frac{4\alpha(1+\beta_M)(a-bc+\alpha S)}{9bk_M} \tag{A66}$$

Substituting these into S, we obtain

$$S = \frac{4\alpha(1+\beta_M)^2(a-bc+\alpha S)}{9bk_M} + \frac{4\alpha(1+\beta_R)^2(a-bc+\alpha S)}{9bk_R} \tag{A67}$$

Therefore,

$$a - bc + \alpha S = \frac{a - bc}{1 - \frac{4\alpha^2(1+\beta_M)^2}{9bk_M} - \frac{4\alpha^2(1+\beta_R)^2}{9bk_R}} \tag{A68}$$

Substituting Equation (A68) into Equations (A65) and (A66), we obtain

$$e_M^{BC*} = \frac{4\alpha(1+\beta_M)(a-bc)}{9bk_M\left[1 - \frac{4\alpha^2(1+\beta_M)^2}{9bk_M} - \frac{4\alpha^2(1+\beta_R)^2}{9bk_R}\right]} \tag{A69}$$

$$e_R^{BC*} = \frac{4\alpha(1+\beta_R)(a-bc)}{9bk_R\left[1 - \frac{4\alpha^2(1+\beta_M)^2}{9bk_M} - \frac{4\alpha^2(1+\beta_R)^2}{9bk_R}\right]} \tag{A70}$$

The corresponding second-stage equilibrium prices and demand are then obtained by substituting e_M^{BC*} and e_R^{BC*} into the balanced-power pricing expressions:

$$w^{BC} = \frac{a + 2bc + \alpha\left[(1+\beta_M)e_M^{BC*} + (1+\beta_R)e_R^{BC*}\right]}{3b} \tag{A71}$$

$$p^{BC} = \frac{2a + bc + 2\alpha\left[(1+\beta_M)e_M^{BC*} + (1+\beta_R)e_R^{BC*}\right]}{3b} \tag{A72}$$

$$q^{BC} = \frac{a - bc + \alpha\left[(1+\beta_M)e_M^{BC*} + (1+\beta_R)e_R^{BC*}\right]}{3} \tag{A73}$$

Proposition 1–5 is thus proved.

Appendix B. Proof of Proposition 6–9

Proof of Proposition 6. Let $T = a - bc > 0$, $A = \frac{\alpha^2(1+\beta_M)^2}{8bk_M}$, $B = \frac{\alpha^2(1+\beta_R)^2}{8bk_R}$.

The equilibrium effort levels under the MN and MC Models can be rewritten as $e_M^{MN*} = \frac{\alpha(1+\beta_M)T}{4bk_M(1-2A-B)}$, $e_R^{MN*} = \frac{\alpha(1+\beta_R)T}{8bk_R(1-2A-B)}$, $e_M^{MC*} = \frac{3\alpha(1+\beta_M)T}{8bk_M(1-3A-3B)}$, $e_R^{MC*} = \frac{3\alpha(1+\beta_R)T}{8bk_R(1-3A-3B)}$.

Hence, $e_M^{MC*} - e_M^{MN*} = \frac{\alpha(1+\beta_M)T}{8bk_M}\left[\frac{3}{1-3A-3B} - \frac{2}{1-2A-B}\right] = \frac{\alpha(1+\beta_M)T(1+3B)}{8bk_M(1-3A-3B)(1-2A-B)} > 0$, and $e_R^{MC*} - e_R^{MN*} = \frac{\alpha(1+\beta_R)T}{8bk_R}\left[\frac{3}{1-3A-3B} - \frac{1}{1-2A-B}\right] = \frac{\alpha(1+\beta_R)T(2-3A)}{8bk_R(1-3A-3B)(1-2A-B)} > 0$.

Under the interior-solution conditions, $1 - 3A - 3B > 0$ and $1 - 2A - B > 0$, so the two inequalities above hold.

Similarly, we have $e_M^{RN*} = \frac{\alpha(1+\beta_M)T}{8bk_M(1-A-2B)}$, $e_R^{RN*} = \frac{\alpha(1+\beta_R)T}{4bk_R(1-A-2B)}$. Therefore, $e_M^{RC*} - e_M^{RN*} = \frac{\alpha(1+\beta_M)T(2-3B)}{8bk_M(1-3A-3B)(1-A-2B)} > 0$, $e_R^{RC*} - e_R^{RN*} = \frac{\alpha(1+\beta_R)T(1+3A)}{8bk_R(1-3A-3B)(1-A-2B)} > 0$.

Finally, define $C = \frac{2\alpha^2(1+\beta_M)^2}{9bk_M}$, $D = \frac{2\alpha^2(1+\beta_R)^2}{9bk_R}$. And we have $e_M^{BN*} = \frac{2\alpha(1+\beta_M)T}{9bk_M(1-C-D)}$, $e_R^{BN*} = \frac{2\alpha(1+\beta_R)T}{9bk_R(1-C-D)}$, $e_M^{BC*} = \frac{4\alpha(1+\beta_M)T}{9bk_M(1-2C-2D)}$, $e_R^{BC*} = \frac{4\alpha(1+\beta_R)T}{9bk_R(1-2C-2D)}$. Thus, $e_M^{BC*} - e_M^{BN*} = \frac{2\alpha(1+\beta_M)T}{9bk_M(1-2C-2D)(1-C-D)} > 0$, $e_R^{BC*} - e_R^{BN*} = \frac{2\alpha(1+\beta_R)T}{9bk_R(1-2C-2D)(1-C-D)} > 0$.

Therefore, $e_M^{MC*} > e_M^{MN*}, e_R^{MC*} > e_R^{MN*}$, $e_M^{RC*} > e_M^{RN*}, e_R^{RC*} > e_R^{RN*}$, $e_M^{BC*} > e_M^{BN*}, e_R^{BC*} > e_R^{BN*}$. □

Proposition 6 is thus proved.

Proof of Proposition 7. For a given power structure, let $\Pi^j(e_M, e_R)$ denote total supply chain profit, where $j \in \{M, R, B\}$ corresponds to the manufacturer-dominated, retailer-dominated, and balanced-power structures, respectively.

Under the MN and RN structures, the total supply chain profit takes the form $\Pi^M(e_M, e_R) = \Pi^R(e_M, e_R) = \frac{3[a-bc+\alpha((1+\beta_M)e_M+(1+\beta_R)e_R)]^2}{16b} - \frac{k_M}{2}e_M^2 - \frac{k_R}{2}e_R^2$.

Under the BN structure, the total supply chain profit is $\Pi^B(e_M, e_R) = \frac{2[a-bc+\alpha((1+\beta_M)e_M+(1+\beta_R)e_R)]^2}{9b} - \frac{k_M}{2}e_M^2 - \frac{k_R}{2}e_R^2$.

By construction, the cooperative model under each power structure chooses (e_M, e_R) to maximize the corresponding total supply chain profit function. In contrast, the non-cooperative model yields effort levels determined by decentralized profit maximization. Therefore, $\Pi^M(e_M^{MC*}, e_R^{MC*}) \geq \Pi^M(e_M^{MN*}, e_R^{MN*}), \Pi^R(e_M^{RC*}, e_R^{RC*}) \geq \Pi^R(e_M^{RN*}, e_R^{RN*})$, $\Pi^B(e_M^{BC*}, e_R^{BC*}) \geq \Pi^B(e_M^{BN*}, e_R^{BN*})$.

Since the interior solution is unique under the maintained parameter conditions, and Proposition 6 has already shown that the cooperative and non-cooperative effort levels are different, the above inequalities are strict. Hence, $\pi_{SC}^{MC*} > \pi_{SC}^{MN*}, \pi_{SC}^{RC*} > \pi_{SC}^{RN*}$, $\pi_{SC}^{BC*} > \pi_{SC}^{BN*}$. □

Proposition 7 is thus proved.

Proof of Proposition 8. Let $G = \alpha[(1+\beta_M)e_M + (1+\beta_R)e_R]$. Conditional on the same aggregate digitalization term G, the retail prices under the three pricing structures can be written as $p^{MN} = \frac{3a+bc+3G}{4b}, p^{RN} = \frac{3a+bc+3G}{4b}, p^{BN} = \frac{2a+bc+2G}{3b}$. Similarly, the corresponding market demands are $q^{MN} = \frac{a-bc+G}{4}, q^{RN} = \frac{a-bc+G}{4}, q^{BN} = \frac{a-bc+G}{3}$. It follows immediately that $p^{MN} = p^{RN}, q^{MN} = q^{RN}$.

Next, consider the difference between the asymmetric and balanced structures: $p^{MN} - p^{BN} = \frac{3a+bc+3G}{4b} - \frac{2a+bc+2G}{3b} = \frac{a-bc+G}{12b} > 0$, which implies $p^{BN} < p^{MN} = p^{RN}$.

Likewise, $q^{BN} - q^{MN} = \frac{a-bc+G}{3} - \frac{a-bc+G}{4} = \frac{a-bc+G}{12} > 0$, so that $q^{BN} > q^{MN} = q^{RN}$.

Therefore, under the same aggregate digitalization term, the manufacturer-dominated and retailer-dominated structures generate the same terminal retail price and market demand, whereas the balanced-power structure yields a lower retail price and a higher market demand. □

Proposition 8 is thus proved.

Proof of Proposition 9. For each model $l \in \{MN, RN, BN, MC, RC, BC\}$, the equilibrium effort levels can be written in the following generic form: $e_M^{l*} = \frac{K_M^l(1+\beta_M)}{1-L_M^l(1+\beta_M)^2-L_R^l(1+\beta_R)^2}, e_R^{l*} = \frac{K_R^l(1+\beta_R)}{1-L_M^l(1+\beta_M)^2-L_R^l(1+\beta_R)^2}$, where $K_M^l > 0$, $K_R^l > 0$, $L_M^l > 0$, and $L_R^l > 0$ are constants determined by the corresponding decision model and the model parameters.

Let $x = 1+\beta_M$ and $y = 1+\beta_R$. Then $e_M^{l*} = \frac{K_M^l x}{1-L_M^l x^2 - L_R^l y^2}, e_R^{l*} = \frac{K_R^l y}{1-L_M^l x^2 - L_R^l y^2}$.

Differentiating e_M^{l*} with respect to β_M yields $\frac{\partial e_M^{l*}}{\partial \beta_M} = \frac{K_M^l[1+L_M^l x^2 - L_R^l y^2]}{(1-L_M^l x^2 - L_R^l y^2)^2} > 0$, because the interior-solution condition implies $1 - L_M^l x^2 - L_R^l y^2 > 0$, and hence $1 + L_M^l x^2 - L_R^l y^2 > 0$. Similarly, $\frac{\partial e_M^{l*}}{\partial \beta_R} = \frac{2K_M^l L_R^l xy}{(1-L_M^l x^2 - L_R^l y^2)^2} > 0$, $\frac{\partial e_R^{l*}}{\partial \beta_M} = \frac{2K_R^l L_M^l xy}{(1-L_M^l x^2 - L_R^l y^2)^2} > 0$, $\frac{\partial e_R^{l*}}{\partial \beta_R} = \frac{K_R^l[1-L_M^l x^2 + L_R^l y^2]}{(1-L_M^l x^2 - L_R^l y^2)^2} > 0$.

Therefore, both firms' equilibrium digital transformation effort levels increase with β_M and β_R.

Now define the aggregate effective digitalization term as $S^{l*} = (1+\beta_M)e_M^{l*} + (1+\beta_R)e_R^{l*}$.

Since e_M^{l*} and e_R^{l*} are both increasing in β_M and β_R, S^{l*} is also increasing in these two spillover coefficients. For each model, market demand can be written as $q^{l*} = \xi_l[a - bc + \alpha S^{l*}]$, where $\xi_l > 0$. Hence, q^{l*} is increasing in β_M and β_R.

Next, the total supply chain profit under each model can be written as $\pi_{SC}^l = \kappa_l[a - bc + \alpha S]^2 - \frac{k_M}{2}e_M^2 - \frac{k_R}{2}e_R^2$, where $\kappa_l > 0$. By the envelope theorem, $\frac{\partial \pi_{SC}^{l*}}{\partial \beta_M} = \frac{\partial \pi_{SC}^l}{\partial \beta_M}\Big|_{e=e^{l*}} = 2\kappa_l \alpha e_M^{l*}[a - bc + \alpha S^{l*}] > 0$, $\frac{\partial \pi_{SC}^{l*}}{\partial \beta_R} = \frac{\partial \pi_{SC}^l}{\partial \beta_R}\Big|_{e=e^{l*}} = 2\kappa_l \alpha e_R^{l*}[a - bc + \alpha S^{l*}] > 0$.

Thus, total supply chain profit increases with β_M and β_R.

Finally, consumer surplus is $CS^{l*} = \frac{(q^{l*})^2}{2b}$, which is increasing in q^{l*}, and social welfare is $SW^{l*} = \pi_{SC}^{l*} + CS^{l*}$. Since both π_{SC}^{l*} and CS^{l*} increase with β_M and β_R, social welfare also increases with these spillover coefficients. □

Proposition 9 is thus proved.

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