

Study on Dual-Channel Green Supply Chain Decision Making Based on Digital Twins

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Abstract. This article constructs four models to explore the impact of digital twins on pricing and profit decisions of dual channel green supply chains under centralized and decentralized decision-making modes. Research has found that without adopting DT, centralized decision-making can lower consumer prices and increase profits for retailers and manufacturers, but the green level of products is not as good as decentralized decision-making. After introducing DT, the centralized decision-making mode can further enhance the green level of products and retailer profits while maintaining price advantages, and even increase manufacturer profits under specific conditions. On the contrary, in the decentralized decision-making mode, although DT improves the green level of products and retailer profits, it may sacrifice the profits of manufacturers. Under different decision-making modes, all parties in the supply chain need to balance the relationship between green level, economic benefits, and technological innovation, optimize the decision-making model, and achieve the dual goals of greening the supply chain and economic benefits.

Keywords: Digital Twin; Dual Channel Green Supply Chain; Centralized Decision-making; Decentralized Decision-Making.

1. Introduction

The Digital Twin (DT) technology provides a new perspective and tool for green supply chain management, enabling managers to simulate, predict, and optimize supply chains without affecting actual operations through real-time data and analysis testing of different strategies and decisions[1]. By integrating data from various links in the supply chain, digital twins have built a transparent collaborative platform, promoting upstream and downstream enterprises to jointly practice green actions and injecting strong impetus into the sustainable development of green supply chains[2].

With the expansion of the research field of green supply chain, emerging issues such as digital transformation, green technology innovation, and social responsibility have gradually entered the research field[3][4]. Numerous studies have shown that the effective implementation of a green supply chain relies on coordination among its members, typically including decision optimization in areas such as product greenness, sales prices, and supply chain performance [5][6]. For example, Han Mengwei et al. [7]proposed a decision model for optimizing pricing and greenness based on consumer reference prices, while Yongfei Li et al. [8] and Gao Juhong et al. [9]explored the optimal pricing and greenness effects of supply chains in centralized and decentralized decision-making scenarios. Based on this, the parameters selected for the model construction in this article also refer to the research aspects mentioned above.

Currently, there is a lack of literature introducing DT to explore channel selection and decision optimization issues, which to some extent limits the recognition and acceptance of DT by enterprises.

2. Problem Description and Underlying Assumptions

In this paper, we consider a secondary green supply chain consisting of a manufacturer and a retailer. The manufacturer dominates the game[10] by selling its goods from the retailer to consumers through traditional offline channels on one hand, and directly to consumers through online channels on the other. Considering the consumers' trust in green products, the manufacturer decides to introduce DT to enhance the transparency and risk resistance of the supply chain.

The variables in the text include the product green level $e > 0$, consumer trust coefficient v , potential market demand a , directly affordable price for consumers p_1 , consumer demand D , cross-elasticity price coefficient b , green product preference coefficient k , retailer margins π_i , network preference coefficient s , the manufacturer's wholesale price to e-tailers in the online channel w_1 , manufacturer margins π_m , and the manufacturer's own retail prices in the online channel w_2 .

3. Model Construction and Analytical Derivation

Proposition 1:

$D_{\text{Traditional}}^{ND} = as - p_1 + bw_2 + kve$, $D_{\text{Online}}^{ND} = a(1-s) - w_2 + bp_1 + kve$, $\pi_i^{ND} = (p_1 - w_1) * D_{\text{Traditional}}^{ND}$, $\pi_m^{ND} = w_1 * D_{\text{Traditional}}^{ND} + w_2 * D_{\text{Online}}^{ND} - 0.5e^2$, $SW = \pi_i^{ND} + \pi_m^{ND}$, $p_1 = \frac{w_1 + as + bw_2 + ekv}{2}$; take this into the manufacturer's profit function, and find the partial derivative of the manufacturer's profit function with respect to w_1, w_2 ; substitute w_1, w_2 for π , and obtain

$$e = \frac{kv(a + bw_1 - 2ab^2 + b^2w_2 - w_1b^3 - w_2b^4 + asb^2 - asb^3)}{2b^3 - 2b^2 - 2b - 2k^2v^2 + 3b^2k^2v^2 + b^3k^2v^2 + 2} \quad (1)$$

Corollary 1:

Decentralized decision making is used when there is no digital twin: $\frac{\partial p_1}{\partial k} > 0, \frac{\partial w_1}{\partial k} > 0, \frac{\partial w_2}{\partial k} > 0, \frac{\partial e}{\partial k} > 0, \frac{\partial \pi_i^N}{\partial k} > 0, \frac{\partial \pi_m^N}{\partial k} > 0$. Centralized decision making is used when there is no digital twin: $\frac{\partial p_1}{\partial k} > 0, \frac{\partial w_2}{\partial k} > 0, \frac{\partial e}{\partial k} > 0, \frac{\partial \pi_i^N}{\partial k} > 0, \frac{\partial \pi_m^N}{\partial k} > 0$. Decentralized decision making is used when digital twins are available: $\frac{\partial p_1}{\partial k} > 0, \frac{\partial w_1}{\partial k} > 0, \frac{\partial w_2}{\partial k} > 0, \frac{\partial e}{\partial k} > 0, \frac{\partial \pi_i^Y}{\partial k} > 0, \frac{\partial \pi_m^Y}{\partial k} > 0$. Centralized decision making is used when digital twins are available: $\frac{\partial p_1}{\partial k} > 0, \frac{\partial w_1}{\partial k} = 0, \frac{\partial w_2}{\partial k} > 0, \frac{\partial e}{\partial k} > 0, \frac{\partial \pi_i^Y}{\partial k} > 0, \frac{\partial \pi_m^Y}{\partial k} > 0$.

Proposition 2:

$D_{\text{Traditional}}^{NC} = as - p_1 + bw_2 + kve$, $D_{\text{Online}}^{NC} = a(1-s) - w_2 + bp_1 + kve$, $\pi_i^{NC} = (p_1 - w_1) * D_{\text{Traditional}}^{NC}$, $\pi_m^{NC} = w_1 * D_{\text{Traditional}}^{NC} + w_2 * D_{\text{Online}}^{NC} - 0.5e^2$, $SW = \pi_i^{NC} + \pi_m^{NC}$, Total profit is derived from p_1, w_1, w_2 and e to give

$$p_1 = \frac{-a(2b + 2s - 2bs + k^2v^2 - 2sk^2v^2)}{4(b+1)(b+k^2v^2-1)} \quad (2)$$

$$w_2 = \frac{-a(2bs - 2s - k^2v^2 + 2sk^2v^2 + 2)}{4(b+1)(b+k^2v^2-1)} \quad (3)$$

$$e = \frac{-akv}{2(b+k^2v^2-1)} \quad (4)$$

Proposition 3:

$D_{\text{Traditional}}^{YD} = as - p_1 + bw_2 + ke$, $D_{\text{Online}}^{YD} = a(1-s) - w_2 + bp_1 + ke$, $\pi_i^{YD} = (p_1 - w_1) * D_{\text{Traditional}}^{YD}$, $\pi_m^{YD} = w_1 * D_{\text{Traditional}}^{YD} + w_2 * D_{\text{Online}}^{YD} - 0.5e^2$, $SW = \pi_i^{YD} + \pi_m^{YD} + e * (D_{\text{Traditional}}^{YD} + D_{\text{Online}}^{YD}) + \frac{(D_1^2 + D_2^2)}{2b}$, the derivative of the retailer margins with respect to p_1 , with the first-order derivative equal to zero, finds the $p_1 = \frac{w_1 + ek + as + bw_2}{2}$.

Proposition 4:

$D_{\text{Traditional}}^{YC} = as - p_1 + bw_2 + ke$, $D_{\text{Online}}^{YC} = a(1-s) - w_2 + bp_1 + ke$, $\pi_i^{YC} = (p_1 - w_1) * D_{\text{Traditional}}^{YC}$, $\pi_m^{YC} = w_1 * D_{\text{Traditional}}^{YC} + w_2 * D_{\text{Online}}^{YC} - 0.5e^2$, $SW = \pi_i^{YC} + \pi_m^{YC} + e * (D_{\text{Traditional}}^{YC} + D_{\text{Online}}^{YC}) + \frac{(D_1^2 + D_2^2)}{2b}$, find the derivative of SW by making the derivative equal to zero:

$$p_1 = \frac{a(1-3b^2-k^2+4bk-2bs+4ks+2sb^2+2sk^2-4bks)}{(4b+4)(2k-b-2bk+b^2+k^2)} \quad (5)$$

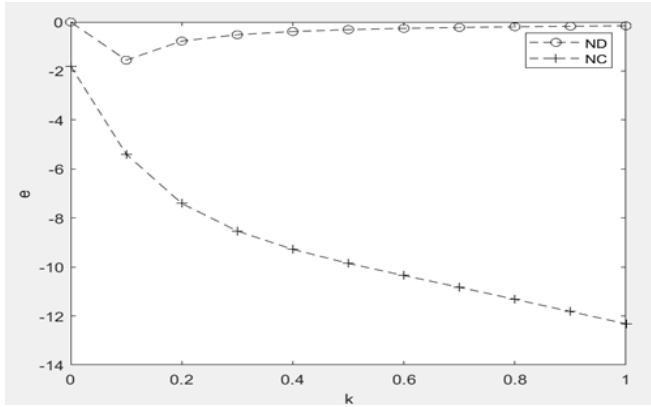
$$w_2 = \frac{a(1-2b+4k-b^2+k^2+2bs-4ks-2sb^2-2sk^2+4bks)}{(4b+4)(2k-b-2bk+b^2+k^2)} \quad (6)$$

$$e = \frac{ab-a-ak}{4k-2b-4bk+2b^2+2k^2} \quad (7)$$

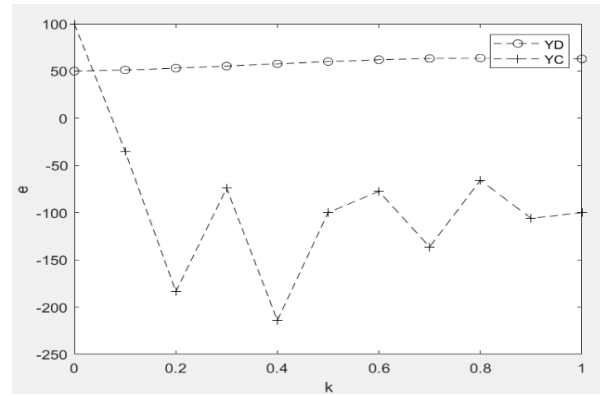
4. Simulation Analysis

1. $p_1^{ND} > p_1^{NC}$ $p_1^{YD} > p_1^{YC}$ Without DT, the price consumers bear is higher in decentralized decision - making. This is because participants focus on self - interests and lack coordination. With the technology, the situation remains the same. $w_2^{ND} > w_2^{NC}$, indicating that decentralized decision-making is higher than centralized decision-making. $w_2^{YD} > w_2^{YC}$: decentralized decision-making is higher than centralized decision-making.

2. $\pi_i^{NC} > \pi_i^{ND}$: centralized decision-making is higher than decentralized decision-making. $\pi_i^{YD} < \pi_i^{YC}$ indicates that centralized decision-making is higher than decentralized decision-making. Without DT, $\pi_m^{NC} > \pi_m^{ND}$ centralized decision - making yields higher manufacturer profits. With it, profit superiority varies before and after an intersection point, showing the tech's impact depends on decision - making modes and stages.

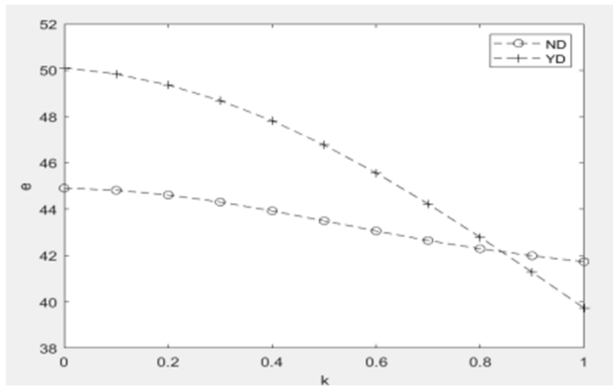


(1)

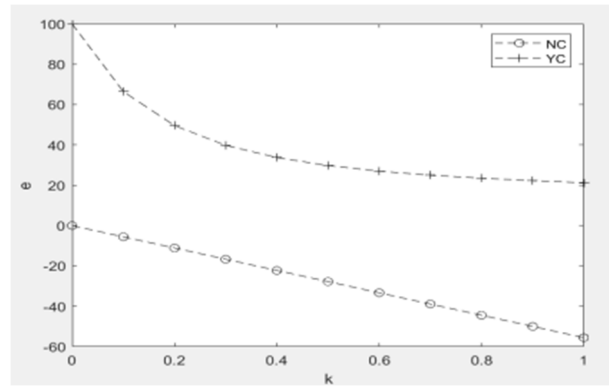


(2)

Fig 1 and 2. without DT, product green level is higher in decentralized decision - making



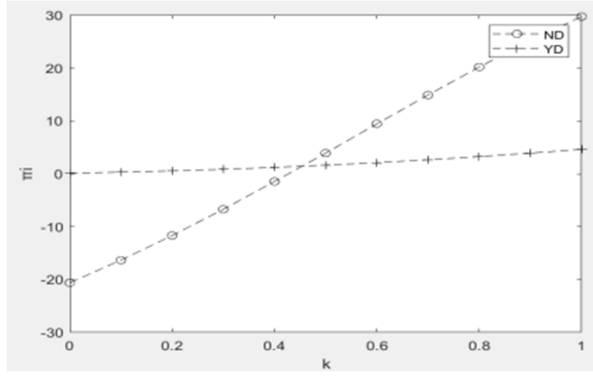
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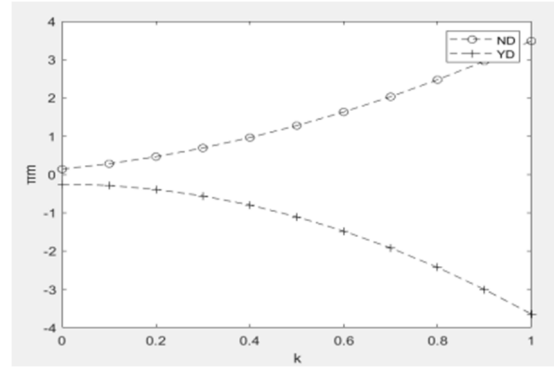
(4)

Fig 3. under decentralized decision making, before the intersection point, DT boosts product green level

Fig 4. Under the centralized decision-making scenario, the green level without adopting DT should always be lower than that in the case of adopting DT



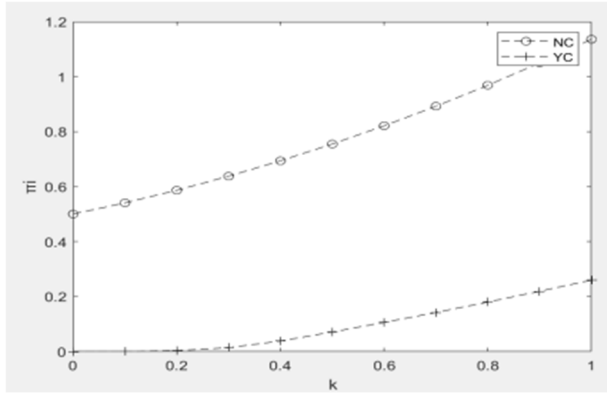
(5)



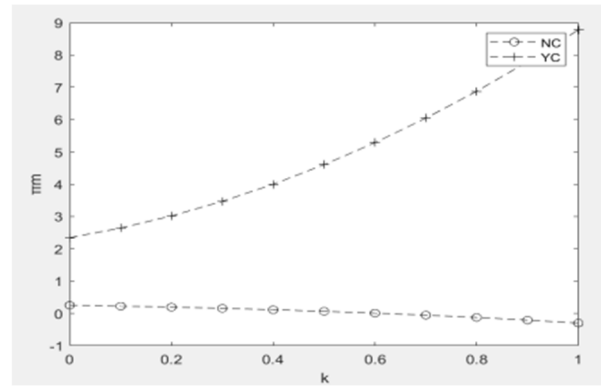
(6)

Fig 5. under decentralized decision - making, before the intersection point, DT increases retailer profits

Fig 6. under decentralized decision - making, manufacturers not adopting DT often have higher profits



(7)



(8)

Fig 7. Under the condition of using centralized decision making, the retailer profit without digital twin technology is greater than the retailer profit with digital twin technology

Fig 8. With digital twin, manufacturers can simulate different production scenarios and strategies in advance to optimize the production process and reduce resource waste and production costs

3. From Figures 1 and 2, without DT, product green level is higher in decentralized decision - making. With it, the superiority of green level between the two modes changes after an intersection point.

4. From Figure 3, under decentralized decision making, before the intersection point, DT boosts product green level. After it, non - digital twin products may be greener. From Figure 4, Under the centralized decision-making scenario, the green level without adopting DT should always be lower than that in the case of adopting DT.

5. From Figure 5, under decentralized decision - making, before the intersection point, DT increases retailer profits. It offers accurate demand forecasts and inventory management. But after the intersection point, non - digital twin retailers may have higher profits. From Figure 6, under decentralized decision - making, manufacturers not adopting DT often have higher profits. This is mainly because digital twin adoption incurs high upfront costs borne independently. Also, in decentralized scenarios, its advantages are hard to fully utilize due to lack of collaboration.

6. From Figure 7, it can be seen that under the condition of using centralized decision making, the retailer profit without digital twin technology is greater than the retailer profit with digital twin technology. From Figure 8, With digital twin, manufacturers can simulate different production

scenarios and strategies in advance to optimize the production process and reduce resource waste and production costs.

5. Conclusion

The findings of this paper have some implications for optimizing green supply chain management: 1)Advantages of centralized decision-making: Without adopting DT technology, centralized decision-making can lower consumer prices, increase profits for retailers and manufacturers, and balance the interests of all parties in the supply chain. After adopting DT technology, the efficiency of centralized decision-making is further improved, consumer prices are reduced, retailer profits are increased, and the green level of products and manufacturer profits are higher than decentralized decision-making under certain conditions, indicating that DT technology can enhance the performance of centralized decision-making mode. 2)Green potential of decentralized decision-making: When DT technology is not adopted, decentralized decision-making can improve the green level of products, and members' independent decision-making is more flexible, which can better respond to market and consumer demand for green products. After adopting DT technology, the green level of products and retailer profits have been further improved, highlighting the potential of DT technology in supporting supply chain members in making environmental decisions. 3)The dual role of DT technology: under centralized decision-making, DT technology improves the green level of products and manufacturer profits, maintains the profit advantage of retailers, and better achieves the greening and economic benefits of the supply chain. Under decentralized decision-making, DT technology improves the green level of products, but may affect manufacturers' profits. This means that when promoting DT technology, consideration should be given to balancing the interests of all parties in the supply chain, especially the profits of manufacturers.

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