Data-driven economy and security*

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Abstract

The purpose of security measures is to reduce the security risks associated with people's economic activities. The methodology for developing such measures is based on global capabilities, including technological and legal ones. The important solutions should be integrated into regional measures, including EU measures. The modern digital economy relies on intelligence, knowledge, and diverse data. The consequences of relevant economic activities are desirable and undesirable products that carry benefits and security risks. Data-driven price wars need predictions, models, simulations, and regulations. The results presented cover these modern data-driven problems and suggest their equilibrium outcomes for both centralized and decentralized scenarios of solutions.

Keywords

data exchange, security, access, generated data, benefit, competition, supply chain, price elasticity

1. Introduction

The EU Data Act is a comprehensive initiative to clarify the challenges and reveal the opportunities provided by data in the EU, aimed at fair access to data and protecting users' rights, as well as ensuring the protection of personal data. The Regulation on harmonized rules on fair access to and use of data, also known as the Data Act, entered into force on 11 January 2024 and became applicable on 12 September 2025. This Act is a key pillar of the European data strategy and a significant contribution to achieving the goal of the EU Digital Decade – promotion of digital transformation. The methodology for developing security measures is based on global capabilities, including technological and legal capabilities in dynamics. The important solutions should be integrated into regional measures, in particular EU measures, based on public-private partnerships or B2B solutions.

The EU Data Law provides for a new set of measures that make more data available to companies, citizens, and public administrations: a) increasing legal certainty; b) mitigating abuses of contractual imbalances; c) public sector access to and use of data; d) switching between providers; e) balancing the interests of data holders and users.

a) Companies and consumers involved in data generation, in particular in the context of the Internet-of-Things (IoTs), benefit from clear rules on permissible data uses and related conditions, while maintaining incentives for data holders to continue investing in the generation of high-quality data. The new rules aim to facilitate the seamless transfer of valuable data between data holders and data users, while preserving their privacy. This will encourage more actors to participate in the data economy, regardless of their size. The European Commission will also develop model contractual clauses to help market participants draw up and conclude fair data-sharing agreements.

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b) Contractual imbalances hinder equitable data sharing. Reducing such imbalances involves safeguarding businesses from unfair contractual terms imposed by a party with a significantly stronger market position.

c) Rules are introduced to allow public sector bodies to access data held by the private sector and use it for specific purposes in the public interest. For example, public sector bodies will be able to request data needed to respond quickly and safely to a public emergency with minimal burden on businesses.

d) The new rules establish a framework for efficient customers switching between different data processing service providers in order to unlock the EU cloud market. This will also contribute to a common framework for effective data interoperability.

e) The new rules review certain aspects of the EU Database Directive, with a particular focus on clarifying the role of the sui generis database right. This right concerns the protection of the content of specific databases, extending its application to databases derived from data generated or acquired through IoT devices. This will ensure that the balance between the interests of data holders and users is consistent with the wider objectives of EU data policy.

2. To data-driven supply chain and economy

The EU Data Law is a powerful driver of innovation and new jobs. It will allow the EU to ensure that it is at the forefront of the latest wave of data-driven developments. Some examples of the practical impact of the new rules on access to and use of data generated by IoT devices include: i) the right to access specific data; ii) cost-effective repair and maintenance of connected products; iii) access to productivity data; iv) improved farming; v) support for the implementation of the Data Act.

i) When purchasing a so-called traditional product, the consumer receives all its components and accessories. However, in the case of connected devices (in particular IoT devices), new data is generated during their normal use. This data complements the product, becoming one of its essential components. The Data Act grants legal entities and individuals the right to access data produced through their use by smart objects, machines, and devices.

ii) If users of connected products choose to share this data with third parties, it will help after-sales service providers (e.g. repair) to improve and innovate their services, promoting fair competition with similar services provided by manufacturers of the products in question. As a result, users of connected products, including consumers, farmers, airlines, construction companies or building owners, will be able to choose more cost-effective repair and maintenance service providers (or perform these tasks themselves), potentially leading to lower prices in the market. Cost-effective repair and maintenance of connected products can extend the life of these products, thereby contributing to the goals of the Green Deal.

iii) The availability of data on the performance of industrial equipment opens up opportunities for efficiency gains. Industries such as manufacturing, agriculture and construction can optimize operational cycles, production lines and supply chain management by relying on machine learning technologies.

iv) In precision agriculture, the application of IoT analytics to data from connected devices allows farmers to analyze real-time information, including weather conditions, temperature, humidity levels, market prices and GPS signals. This analysis provides valuable insights to optimize and increase crop yields. Improved understanding of real-time data supports more effective farm planning, helping farmers make informed decisions about resource allocation.

v) The Data Act applies from 12 September 2025, marking an important step towards building a fair and innovative European data economy. Leading management consulting firm Gartner predicts that organizations that facilitate data sharing will outperform their competitors across most business value metrics.

In addition, new legislation such as the German Act on Corporate Due Diligence Obligations in Supply Chains (LkSG), the EU Corporate Sustainability Reporting Directive (CSRD) 2022/2464, the EU Corporate Sustainability Due Diligence Directive (CSDDD) 2024/1760 require organizations to collect data on their direct and indirect suppliers and to ensure that they and their suppliers do not engage in activities that harm the environment or contribute to inhumane working conditions.

The LkSG Supply Chain Act is a German law that requires every company to monitor human rights and environmental risks within its own business operations, its supply chains, including its direct and indirect suppliers. The law requires a company to conduct a contract analysis in all its supply chains (value creation) to identify risks to human rights and the environment and requires the company to take measures to address the risks identified. This involves implementing due diligence processes to identify, prevent, mitigate and eliminate potential negative consequences of such risks, and to take appropriate measures in a timely manner. A company's due diligence obligation is to establish an appropriate risk management system. Companies must publish an annual report containing the results of their efforts to conduct the aforementioned contract analysis in their supply chains. Realizing the positive intentions of the LkSG and CSRD, overcoming the additional costs of bureaucracy and inter-organizational cooperation requires organizations to collect data from many parties, such as suppliers, government agencies, customers, NGOs, or informants.

The Cologne Institute for Economic Research (Das Institut der deutschen Wirtschaft Köln e. V. (IW); headquartered in Cologne and offices in Berlin and Brussels; founded in 1951, employer-oriented, funded by business associations and companies) confirms that most companies are now obliged to provide information to their suppliers or customers who are subject to the LkSG. The sponsors of IW Köln are the BDA and the Federation of German Industry (Bundesverband der Deutschen Industrie (BDI); founded on February 4, 1919, as the Reichsverband der Deutschen Industrie (RDI) of the Weimar Republic (1918–1933)). This provision of information can be particularly challenging, for example, in the automotive industry, which is characterized by extremely complex supply chains, where car manufacturers employ thousands of direct suppliers and the number of direct suppliers exceeds the number of indirect suppliers: today the Mercedes-Benz Group reports around 40,000 suppliers and the BMW Group around 12,000 suppliers. At the same time, car manufacturers are tasked with ensuring transparency and continuously monitoring their (indirect) suppliers for risks related to environmental or human rights violations. Ensuring transparency, continuously monitoring their (indirect) suppliers and promoting cooperation across supply chains are challenging for everyone involved in car production. For example, it is not easy for BMW to monitor all its suppliers in some parts of the world, where the risks associated with environmental or human rights violations exceed those in the EU.

3. Complementarity of online transactions

Attention should be paid to the issues of customer service levels, reconciliation of conflicts between demand and supply in supply chains (SCs), using common decision-making objectives and unique interrelationships of complementary products [1]. Based on game theory, it is possible to analyze the pricing strategies of complementary products in a three-level two-channel SC, the relationship between pricing and service levels, and the optimization of performance in different channels [2]. With the continuous development and deepening of economic globalization, new Internet-based driving forces are deeply integrated with various industries [3]. The combination of the Internet, online payments, and logistics has greatly accelerated the development of global online marketing [4]. In the context of economic downturn and intensified market competition, manufacturers of products in the SC establish online direct sales channels to maintain competitive advantages and expand their market shares [5]. However, the establishment of online direct sales channels by manufacturers has led to price conflicts with retailers due to the sale of identical products through

the abovementioned channels and traditional retail sales channels. For example, when a certain enterprise sells products at promotional prices on online platforms, its offline distributors are often forced to reduce their prices as well, which leads to two-way pressure on the profits of sales channels.

Information age consumers demand lower prices for goods in retail outlets and demand improved service levels for these goods. Similarly, there is a positive service externality on complementary products, where improving the service level of one product increases the costs of producing it and, accordingly, benefits the profits of the producers of the competing product. For example, when smart door lock manufacturers invest more resources in improving their cloud-based customer service systems, the suppliers of the corresponding smart home support systems will simultaneously gain more users. In this case, the costs of service will be borne by the smart door lock manufacturers, not by the suppliers. However, in highly competitive markets, rational decision makers will not increase their own costs to increase the profits of their competitors. Therefore, conflicts will also arise in dual-channel SCs of services. Determining prices and service levels is a relevant issue for businesses. Modern SCs are increasingly using real-time data from online platforms and offline stores to make pricing and inventory decisions simultaneously or in parallel.

The linear demand function in SC can intuitively reflect cross-price effects in dual-channel SC. In addition, empirical studies have shown the existence of relevant products for which the demand exhibits a linear dependence on price. A linear demand function in price is also flexible and concise, simplifying the creation of models and taking into account other demand factors. For example, the impact of service quality on demand has been widely studied using a linear demand model in the context of dual-channel SCs. Dual-channel SCs mainly use centralized and decentralized strategies that are used to study game behavior between manufacturers and retailers. Regardless of the approaches, focusing on product pricing and corporate profits remains the main task of SC system theory and practice. Analysis of information on dual-channel SC aspects, complementary products, and service quality levels reveals some implications of any combination of these aspects. The combination of complementary product pricing and service value investment aspects of dual-channel SC systems is noteworthy. Suppose that manufacturers in a SC produce two complementary products, one of which is sold through direct online sales channels and the other is sold in bulk to retailers for distribution through traditional retail channels. Since both parties (channels) in the SC seek to maximize their profits, a decrease in the sales price of one product will lead to an increase in demand in both channels. A price decrease may lead to a decrease in profits for the party that lowered its prices, as well as to an increase in demand and profits for the other party that did not change its prices and benefited from a positive externality (spillover effect) for complementary products. Thus, price conflicts arise in dual-channel SCs with complementary products. The aforementioned conflicts between manufacturers and retailers as sellers in the SC can be mitigated by establishing direct online sales channels between both parties and reducing unnecessary competition [2], building a two-channel three-tier SC system that includes one manufacturer, retailer and consumers. The special relationships between complementary products lead to positive demand externalities, as well as free-riding behavior among service users. Complementary products in the SC have the potential to mitigate conflicts between dual channels of service delivery. Pricing decisions and investment in complementary products are made within the dual-channel supply chain. Innovative systematic studies on the coordination of pricing and services of complementary products under different decision-making authority structures are needed, which simultaneously take into account price elasticity, cross-price elasticity, and service externalities [2]. The concept of fraudulent returns is introduced into the dual-channel SC system, based on an analysis of common strategies used by manufacturers to establish direct online sales channels and sales of products through traditional retail stores. The impact of the risk attitudes of

both sides of the channel is investigated: optimal prices for risk aversion are lower than prices for risk neutrality.

4. The three-tier supply chain model

Let a dual-channel, three-tier supply chain include manufacturers, retailers, and consumers, where manufacturers not only supply goods to retailers but also create online direct sales channels to market complementary products of these goods: the manufacturer supplies the good B to a retailer (seller, intermediary) for sale through traditional retail channels at a wholesale price w, who in turn supplies this good to consumers at a traditional retail price p_B, to whom the manufacturer also simultaneously directly through online direct sales channels sells the good A at a price p_A. Assume that the manufacturer produces two complementary products A and B. In many cases of dual-channel trade, especially for digital goods or products with low marginal cost, production costs are insignificant compared to the distribution and pricing effects [6]. Thus, here, without loss of generality, we assume that the production costs of the product A are insignificant, emphasizing the influence of pricing strategies and elasticity effects.

Without accounting for the production costs of the product A, we will focus exclusively on the production costs c of the product B that satisfy the condition $c < w$. The retail price p_B of the product B is set by the retailer, and the direct sales price p_A of the product A is set by the manufacturer; the production costs of the product A do not exceed p_A.

The demand for the direct online sales channel [7, 8] can be expressed as

$$D_m = a - \alpha_1 p_A - \beta_1 p_B,$$

where: a – the potential market size of the product A; α_1 – the (own) coefficient of elasticity of the price effect of the product A on the demand for this product; β_1 – the coefficient of elasticity of the cross-price effect of the product on the demand for this product.

The demand for the traditional retail channel is

$$D_r = b - \alpha_2 p_B - \beta_2 p_A,$$

where: b – the potential market size of the product B; α_2 – the (own) coefficient of elasticity of the price effect of the product B on the demand for this product; β_2 – coefficient of elasticity of cross-price impact of the product A on the demand for the product B.

Suppose that the coefficient of cross-price elasticity is less than the coefficient of own price elasticity: $\alpha_i > \beta_i > 0$, $i = 1,2$. The profit of the manufacturer is

$$\pi_m = p_A D_m + (w - c) D_r,$$

and that of the retailer –

$$\pi_r = (p_B - w) D_r.$$

In the centralized decision-making scenario, the manufacturer and the retailer are considered as a single entity. Based on the premise of maximizing the profit $\pi_{sc} \doteq \pi_m + \pi_r$ of the supply chain, the manufacturer and the retailer make pricing decisions, maximizing the joint profit

$$p_A D_m + (w - c) D_r + (p_B - w) D_r = p_A D_m + (p_B - c) D_r. \quad (1)$$

Let's find the pricing strategy in the centralized scenario. Maximizing the value of the profit π_{sc} of the supply chain, it is necessary to prove that the function $\pi_{sc}(p_A, p_B)$ is a concave function

with respect to (p_A, p_B). A function $f(x, y)$ is concave with respect to (x, y), if its Hessian matrix

$$H = \begin{bmatrix} \partial^2 f / \partial x^2 & \partial^2 f / \partial x \partial y \\ \partial^2 f / \partial x \partial y & \partial^2 f / \partial y^2 \end{bmatrix}$$

of second-order partial derivatives is negative semidefinite everywhere in its domain, i.e. all its eigenvalues are non-positive. For strict concavity, the Hessian matrix must be negative definite. The condition for the function to be concave is the positivity of the determinant of its Hessian matrix. Let us calculate the necessary derivatives:

$$\partial D_m / \partial p_A = -\alpha_1, \qquad \partial D_r / \partial p_A = -\beta_2,$$

$$\partial \pi_{sc}(p_A, p_B) / \partial p_A = D_m + p_A \partial D_m / \partial p_A + (p_B - c) \partial D_r / \partial p_A = ¿$$

$$¿\, a - \alpha_1 p_A - \beta_1 p_B - \alpha_1 p_A - \beta_2 (p_B - c) = a + \beta_2 c - 2\alpha_1 p_A - (\beta_1 + \beta_2) p_B;$$

$$\partial D_m / \partial p_B = -\beta_1, \qquad \partial D_r / \partial p_B = -\alpha_2,$$

$$\partial \pi_{sc}(p_A, p_B) / \partial p_B = p_A \partial D_m / \partial p_B + D_r + (p_B - c) \partial D_r / \partial p_B = ¿$$

$$¿\, b - \alpha_2 p_B - \beta_2 p_A - \beta_1 p_A - \alpha_2 (p_B - c) = b + \alpha_2 c - (\beta_1 + \beta_2) p_A - 2\alpha_2 p_B;$$

$$\partial^2 \pi_{sc}(p_A, p_B) / \partial (p_A)^2 = -2\alpha_1; \qquad \partial^2 \pi_{sc}(p_A, p_B) / \partial (p_B)^2 = -2\alpha_2;$$

$$\partial^2 \pi_{sc}(p_A, p_B) / \partial p_A \partial p_B = -\beta_1 - \beta_2 = \partial^2 \pi_{sc}(p_A, p_B) / \partial p_B \partial p_A.$$

Then the Hessian matrix for the joint profit function $\pi_{sc}(p_A, p_B)$ of a two-channel supply chain for complementary products under centralized management has the form

$$H = \begin{bmatrix} -2\alpha_1 & -(\beta_1 + \beta_2) \\ -(\beta_1 + \beta_2) & -2\alpha_2 \end{bmatrix},$$

whose determinant is

$$det(H) = 4\alpha_1 \alpha_2 - (\beta_1 + \beta_2)^2$$

and is positive by the assumption $\alpha_i > \beta_i > 0$, $i = 1,2$. Therefore, the profit $\pi_{sc}(p_A, p_B)$ of a two-channel supply chain for complementary products has a joint maximum value with respect to (p_A, p_B) [9]. Then, the system of equations

$$0 = \partial \pi_{sc}(p_A, p_B) / \partial p_A = a + \beta_2 c - 2\alpha_1 p_A - (\beta_1 + \beta_2) p_B,$$

$$0 = \partial \pi_{sc}(p_A, p_B) / \partial p_B = b + \alpha_2 c - (\beta_1 + \beta_2) p_A - 2\alpha_2 p_B$$

implies the optimal prices under centralized decision-making follow:

$$0 = 2\alpha_2 [a + \beta_2 c - 2\alpha_1 p_A - (\beta_1 + \beta_2) p_B], \qquad 0 = -(\beta_1 + \beta_2)[b + \alpha_2 c - (\beta_1 + \beta_2) p_A - 2\alpha_2 p_B];$$

$$0 = 2\alpha_2 [a + \beta_2 c - 2\alpha_1 p_A] - (\beta_1 + \beta_2)[b + \alpha_2 c - (\beta_1 + \beta_2) p_A] =$$

$$= 2\alpha_2 (a + \beta_2 c) - 4\alpha_1 \alpha_2 p_A - (\beta_1 + \beta_2)(b + \alpha_2 c) + (\beta_1 + \beta_2)^2 p_A,$$

$$p_A^c = [2\alpha_2 (a + \beta_2 c) - (\beta_1 + \beta_2)(b + \alpha_2 c)] / [4\alpha_1 \alpha_2 - (\beta_1 + \beta_2)^2];$$

$$0 = (\beta_1 + \beta_2)[a + \beta_2 c - 2\alpha_1 p_A - (\beta_1 + \beta_2) p_B],$$

$$0 = -2\alpha_1 [b + \alpha_2 c - (\beta_1 + \beta_2) p_A - 2\alpha_2 p_B];$$

$$0=(\beta_1+\beta_2)[a+\beta_2 c-(\beta_1+\beta_2)p_B]-2\alpha_1[b+\alpha_2 c-2\alpha_2 p_B]=$$

$$=(\beta_1+\beta_2)(a+\beta_2 c)-(\beta_1+\beta_2)^2 p_B-2\alpha_1(b+\alpha_2 c)+4\alpha_1\alpha_2 p_B,$$

$$p_B^c=[2\alpha_1(b+\alpha_2 c)-(\beta_1+\beta_2)(a+\beta_2 c)]/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2].$$

5. Decentralized decision-making scenario

Let us find the pricing strategy under the manufacturer leadership scenario and move on to the Stackelberg decision-making scenario, where the manufacturer is the channel leader and the retailer is its follower [10–12]. Thus, the manufacturer sets wholesale and online direct sales prices for complementary products based on the retailer's price response, seeking to maximize its own profit: first, the manufacturer sets wholesale and online prices based on the retailer's optimal price response, and then the retailer maximizes its profit by setting its price based on the manufacturer's wholesale and online prices. The decision-making model is given by the maximization of the producer's profit

$$\pi_m(p_A,w)=p_A D_m+(w-c)D_r=p_A(a-\alpha_1 p_A-\beta_1 p_B)+(w-c)(b-\alpha_2 p_B-\beta_2 p_A) \quad (1)$$

subject to the maximization of the retailer's profit

$$\pi_r(p_B)=(p_B-w)D_r. \quad (2)$$

The necessary condition of the first-order extremum for the function $\pi_r(p_B)$

$$0=\partial\pi_r/\partial p_B=(p_B-w)\partial D_r/\partial p_B+D_r=-\alpha_2(p_B-w)+b-\alpha_2 p_B-\beta_2 p_A$$

implies the retailer's reaction function for the traditional retail price

$$p_B=(\alpha_2 w+b-\beta_2 p_A)/(2\alpha_2),$$

using which one can derive the producer's price p_A for the direct online sales channel and the wholesale price w for the complementary product:

$$0=\partial\pi_m/\partial p_A=a-\alpha_1 p_A-\beta_1 p_B+p_A(-\alpha_1-\beta_1\partial p_B/\partial p_A)+(w-c)(-\alpha_2\partial p_B/\partial p_A-\beta_2)=$$

$$¿\, a-2\alpha_1 p_A-\beta_1 p_B-[\beta_1 p_A+\alpha_2(w-c)]\partial p_B/\partial p_A-\beta_2(w-c)=$$

$$¿\, a-2\alpha_1 p_A-\beta_1 p_B+\beta_2[\beta_1 p_A+\alpha_2(w-c)]/(2\alpha_2)-\beta_2(w-c)=$$

$$=\{2\alpha_2[a-\beta_2(w-c)-2\alpha_1 p_A-\beta_1 p_B]+\beta_2[\beta_1 p_A+\alpha_2(w-c)]\}/(2\alpha_2)=$$

$$=\{2\alpha_2(a-\beta_1 p_B)-\alpha_2\beta_2(w-c)+p_A(\beta_1\beta_2-4\alpha_1\alpha_2)\}/(2\alpha_2)=$$

$$=\{2\alpha_2 a-2\alpha_2\beta_1 p_B-\alpha_2\beta_2(w-c)+p_A(\beta_1\beta_2-4\alpha_1\alpha_2)\}/(2\alpha_2)=$$

$$=\{2\alpha_2 a-\beta_1(\alpha_2 w+b-\beta_2 p_A)-\alpha_2\beta_2(w-c)+p_A(\beta_1\beta_2-4\alpha_1\alpha_2)\}/(2\alpha_2)=$$

$$=\{2\alpha_2 a-\beta_1(\alpha_2 w+b)-\alpha_2\beta_2(w-c)+p_A(2\beta_1\beta_2-4\alpha_1\alpha_2)\}/(2\alpha_2)=¿$$

$$=\{2\alpha_2 a-\beta_1 b-(\beta_1+\beta_2)\alpha_2 w+\beta_2\alpha_2 c+2p_A(\beta_1\beta_2-2\alpha_1\alpha_2)\}/(2\alpha_2),$$

where $\partial p_B/\partial p_A=-\beta_2/(2\alpha_2)$;

$$0=\partial\pi_m/\partial w=-p_A\beta_1\partial p_B/\partial w+b-\alpha_2 p_B-\beta_2 p_A-(w-c)\alpha_2\partial p_B/\partial w=¿$$

$$=[-\beta_1 p_A+2(b-\alpha_2 p_B-\beta_2 p_A)-\alpha_2(w-c)]/2=[-(\beta_1+2\beta_2)p_A+2(b-\alpha_2 p_B)-\alpha_2(w-c)]/2=$$

$$=[-(\beta_1+2\beta_2)p_A+2[b-(\alpha_2 w+b-\beta_2 p_A)/2]-\alpha_2(w-c)]/2=$$

$$=[-(\beta_1+2\beta_2)p_A+2b-(\alpha_2 w+b-\beta_2 p_A)-\alpha_2(w-c)]/2=[-(\beta_1+\beta_2)p_A+b-2\alpha_2 w+\alpha_2 c]/2$$

,

where $\partial p_B/\partial w=1/2$. Then the system of equations

$$2\alpha_2 a-\beta_1 b-(\beta_1+\beta_2)\alpha_2 w+\beta_2\alpha_2 c+2p_A(\beta_1\beta_2-2\alpha_1\alpha_2)=0,$$
$$-(\beta_1+\beta_2)p_A-2\alpha_2 w+b+\alpha_2 c=0$$

implies the Stackelberg equilibrium prices p_A, w:

$$4\alpha_2 a-2\beta_1 b-2(\beta_1+\beta_2)\alpha_2 w+2\beta_2\alpha_2 c+4p_A(\beta_1\beta_2-2\alpha_1\alpha_2)=0,$$
$$(\beta_1+\beta_2)^2 p_A+2\alpha_2(\beta_1+\beta_2)w-(b+\alpha_2 c)(\beta_1+\beta_2)=0;$$

$$0=4\alpha_2 a-2\beta_1 b+2\beta_2\alpha_2 c+4p_A(\beta_1\beta_2-2\alpha_1\alpha_2)+(\beta_1+\beta_2)^2 p_A-(b+\alpha_2 c)(\beta_1+\beta_2),$$

$$p_A^S=[-4\alpha_2 a+2\beta_1 b-2\beta_2\alpha_2 c+(b+\alpha_2 c)(\beta_1+\beta_2)]/[4(\beta_1\beta_2-2\alpha_1\alpha_2)+(\beta_1+\beta_2)^2];$$

$$(\beta_1+\beta_2)[2\alpha_2 a-\beta_1 b-(\beta_1+\beta_2)\alpha_2 w+\beta_2\alpha_2 c+2p_A(\beta_1\beta_2-2\alpha_1\alpha_2)]=0,$$
$$2(2\alpha_1\alpha_2-\beta_1\beta_2)[-(\beta_1+\beta_2)p_A-2\alpha_2 w+b+\alpha_2 c]=0;$$

$$0=(\beta_1+\beta_2)[2\alpha_2 a-\beta_1 b-(\beta_1+\beta_2)\alpha_2 w+\beta_2\alpha_2 c]+2(2\alpha_1\alpha_2-\beta_1\beta_2)(-2\alpha_2 w+b+\alpha_2 c)=0$$

,

$$(\beta_1+\beta_2)^2\alpha_2 w+4(2\alpha_1\alpha_2-\beta_1\beta_2)\alpha_2 w=(\beta_1+\beta_2)(2\alpha_2 a-\beta_1 b+\beta_2\alpha_2 c)+2(2\alpha_1\alpha_2-\beta_1\beta_2)(b+\alpha_2 c)$$

,

$$w^S=[(\beta_1+\beta_2)(2\alpha_2 a-\beta_1 b+\beta_2\alpha_2 c)+2(2\alpha_1\alpha_2-\beta_1\beta_2)(b+\alpha_2 c)]/\{\alpha_2[(\beta_1+\beta_2)^2+¿$$
$$+4(2\alpha_1\alpha_2-\beta_1\beta_2)]\}.$$

Knowing the calculated values of p_A^S, w^S, we can calculate

$$p_B^S=(\alpha_2 w^S+b-\beta_2 p_A^S)/(2\alpha_2),$$

where we assume that the market data (parameters) a, b, c, α_i, β_i, $i=1,2$, guarantee the positivity of the prices p_A^S, p_B^S, w^S. The dependence of p_B^S on these parameters can be investigated by numerical simulations [13–15]. Thus, in the Stackelberg game, where the leader is the manufacturer with a profit defined by equation (1), reaches its maximum value at prices (p_A^S, w^S), and the retailer's profit, defined by equation (2), reaches its maximum value at price p_B^S. This conclusion can be illustrated by a simple example. For example, the strategy of smartphones and accessories often faces tensions between flagship online stores and offline resellers. When the manufacturer sets a wholesale price w and an online price p_A, and retailers adjust their prices p_B based on local demand, the result is that offline retailers are sometimes forced to lower their prices, demonstrating the coordination problem to which this model is devoted. Let us analyze the consequences for the equilibrium found. First of all, there is a positive correlation between the wholesale price w^S and the potential market demand a of the manufacturer, i.e., as the potential market demand a of the manufacturer increases, the wholesale price w^S of its complementary goods will gradually increase:

$$\partial w^S / \partial a = 2(\beta_1+\beta_2)/[(\beta_1+\beta_2)^2+4(2\alpha_1\alpha_2-\beta_1\beta_2)]>0.$$

There is also a positive correlation between the wholesale price w^S and the potential market demand b of the retailer, i.e., as the potential market demand b of the retailer increases, the wholesale price w^S of the manufacturer for the product may gradually increase:

$$\partial w^S / \partial b = [-\beta_1(\beta_1+\beta_2)+2(2\alpha_1\alpha_2-\beta_1\beta_2)]/\{\alpha_2[(\beta_1+\beta_2)^2+4(2\alpha_1\alpha_2-\beta_1\beta_2)]\},$$

where the denominator is positive and the numerator

$$-\beta_1(\beta_1+\beta_2)+2(2\alpha_1\alpha_2-\beta_1\beta_2)=-(\beta_1)^2-3\beta_1\beta_2+3\alpha_1\alpha_2+\alpha_1\alpha_2.$$

is also positive under the intuitive condition $\alpha_i > max\{\beta_1, \beta_2\}$, $i=1,2$.

6. Equilibrium price sensitivities to the demand data

In the centralized scenario, the prices of both parties (the manufacturer and the retailer) increase with their own potential market demand (a and b), but decrease with the demand of the other party, i.e., as the potential market demand a of the manufacturer (the potential market demand b of the retailer) increases, the manufacturer's selling price p_A^c (the retailer's selling price p_B^c) increases as well:

$$\partial p_A^c / \partial a = 2\alpha_2/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]>0;$$

$$\partial p_A^c / \partial b = \partial p_B^c / \partial a = -(\beta_1+\beta_2)/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]<0;$$

$$\partial p_B^c / \partial b = 2\alpha_1/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]>0.$$

In a decentralized decision-making scenario, the prices p_A^S, p_B^S of both parties may decrease with their own potential demand (a, b), but may increase with the potential demand of the other party:

$$\partial p_A^S / \partial a = -4\alpha_2/[4(\beta_1\beta_2-2\alpha_1\alpha_2)+(\beta_1+\beta_2)^2],$$

where the numerator is negative and the denominator is positive under $2\alpha_1\alpha_2>(\beta_1)^2+(\beta_2)^2$ and the abovementioned condition $\alpha_i > max\{\beta_1, \beta_2\}$, $i=1,2$,

$$8\alpha_1\alpha_2>4\beta_1\beta_2+(\beta_1+\beta_2)^2=6\beta_1\beta_2+(\beta_1)^2+(\beta_2)^2;$$

$$\partial p_A^S / \partial b = (3\beta_1+\beta_2)/[4(\beta_1\beta_2-2\alpha_1\alpha_2)+(\beta_1+\beta_2)^2],$$

where the denominator is positive under this condition and the numerator is positive;

$$\partial p_B^c / \partial b = 2\alpha_1/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2],$$
$$\partial p_B^S / \partial a = [\alpha_2 \partial w^S / \partial a - \beta_2 \partial p_A^S / \partial a]/(2\alpha_2)>0,$$

where $\partial w^S / \partial a > 0$, $\partial p_A^S / \partial a < 0$;

$$\partial p_B^S / \partial b = [\alpha_2 \partial w^S / \partial b - \beta_2 \partial p_A^S / \partial b + 1]/(2\alpha_2)<0$$

for $\alpha_2 \partial w^S / \partial b - \beta_2 \partial p_A^S / \partial b + 1 < 0$, where $\partial w^S / \partial b > 0$, $\partial p_A^S / \partial b > 0$.

Thus, in a centralized scenario, the price of each party may increase with its own potential demand and decrease with the potential demand of the other party.

In the centralized scenario, the manufacturer's direct online sales price p_A^c is negatively correlated with the product's price elasticity coefficient α_1, i.e., as the price elasticity coefficient α_1 of the direct sales product increases, the manufacturer tends to lower its selling price p_A^c:

$$\partial p_A^c / \partial \alpha_1 = -4\alpha_2[2\alpha_2(a+\beta_2 c)-(\beta_1+\beta_2)(b+\alpha_2 c)]/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]^2 < 0,$$

where the denominator is positive and the sign of the numerator is opposite to the positive under the intuitively understandable (approximate) condition $a+\beta_2 c = b+\alpha_2 c$ of the sign of the numerator expression

$$2\alpha_2(a+\beta_2 c)-(\beta_1+\beta_2)(b+\alpha_2 c).$$

The retailer's retail price p_B^c for complementary products is positively correlated with the manufacturer's product's price elasticity α_1 coefficient:

$$\partial p_B^c / \partial \alpha_1 = -4\alpha_2[2\alpha_1(b+\alpha_2 c)-(\beta_1+\beta_2)(a+\beta_2 c)]/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]^2 > 0,$$

where the denominator is positive and the sign of the numerator is opposite to the negative under the intuitively understandable (approximate) condition $a+\beta_2 c = b+\alpha_2 c$ of the sign of the numerator expression

$$-2\alpha_1(b+\alpha_2 c)+(\beta_1+\beta_2)(a+\beta_2 c).$$

Therefore, using direct sales with high price elasticity can serve for an overall competitive advantage. In the centralized scenario, as the price elasticity α_2 of complementary goods sold by a retailer increases, the retailer will reduce the selling price p_B^c:

$$\partial p_B^c / \partial \alpha_2 = 2\alpha_1\{c[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]-2[2\alpha_1(b+\alpha_2 c)-(\beta_1+\beta_2)(a+\beta_2 c)]\}/$$

$$/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]^2 < 0,$$

where the denominator is positive and the sign of the numerator is the sign of expression

$$c[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]-2[2\alpha_1(b+\alpha_2 c)-(\beta_1+\beta_2)(a+\beta_2 c)] =$$

$$= 4\alpha_1\alpha_2 c-(\beta_1+\beta_2)^2 c-4\alpha_1(b+\alpha_2 c)+2(\beta_1+\beta_2)(a+\beta_2 c) =$$

$$= -(\beta_1+\beta_2)^2 c-4\alpha_1 b+2(\beta_1+\beta_2)(a+\beta_2 c) = -4\alpha_1 b+(\beta_1+\beta_2)(2a+2\beta_2 c-\beta_1 c-\beta_2 c) =$$

$$¿ -4\alpha_1 b+(\beta_1+\beta_2)[2a+(\beta_2-\beta_1)c],$$

which is negative for $4\alpha_1 b > (\beta_1+\beta_2)[2a+(\beta_2-\beta_1)c]$, when the values of b, α_1 are sufficiently large. For example, in the case of daily necessities, when the price elasticity of a product increases, the retailer will take into account the risk of consumers switching to other brands and therefore generally reduce the selling price accordingly. Conversely, for $4\alpha_1 b < (\beta_1+\beta_2)[2a+(\beta_2-\beta_1)c]$, as the price elasticity α_2 of complementary goods increases, the retailer will increase the selling price p_B^c. For example, in the case of luxury goods, when the price elasticity of a product increases, the retailer will take into account the purchasing preferences of buyers of such goods and increase prices to match the purchasing psychology of consumers. In both scenarios, the producer price in direct sales exhibits the opposite price behavior compared to the retailer price:

$$p_A^c = [2\alpha_2(a+\beta_2 c)-(\beta_1+\beta_2)(b+\alpha_2 c)]/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2];$$

$$\partial p_A^c / \partial \alpha_2 = \{[2(a+\beta_2 c)-(\beta_1+\beta_2)c)][4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]-¿$$

$$-4\alpha_1[2\alpha_2(a+\beta_2 c)-(\beta_1+\beta_2)(b+\alpha_2 c)]\}/[4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]^2,$$

where the denominator is positive and the numerator

$$[2(a+\beta_2 c)-(\beta_1+\beta_2)c)][4\alpha_1\alpha_2-(\beta_1+\beta_2)^2]-¿$$

$$=8\alpha_1\alpha_2(a+\beta_2 c)-4\alpha_1\alpha_2(\beta_1+\beta_2)c+(\beta_1+\beta_2)^3 c-2(a+\beta_2 c)(\beta_1+\beta_2)^2-¿$$

$$-8\alpha_1\alpha_2(a+\beta_2 c)+4\alpha_1(\beta_1+\beta_2)(b+\alpha_2 c)=$$

$$=(\beta_1+\beta_2)[-4\alpha_1\alpha_2 c+(\beta_1+\beta_2)^2 c-2(a+\beta_2 c)(\beta_1+\beta_2)+4\alpha_1(b+\alpha_2 c)]$$

has the sign of expression

$$(\beta_1+\beta_2)^2 c-2(a+\beta_2 c)(\beta_1+\beta_2)+4\alpha_1(b+\alpha_2 c-\alpha_2 c)=$$

$$=(\beta_1+\beta_2)(\beta_1 c+\beta_2 c-2a-2\beta_2 c)+4\alpha_1 b=(\beta_1+\beta_2)[(\beta_1-\beta_2)c-2a]+4\alpha_1 b,$$

which is positive for

$$(\beta_1+\beta_2)[(\beta_1-\beta_2)c-2a]+4\alpha_1 b>0,$$

i.e., for the above condition $4\alpha_1 b>(\beta_1+\beta_2)[2a+(\beta_2-\beta_1)c]$, and it is negative for the opposite condition $4\alpha_1 b<(\beta_1+\beta_2)[2a+(\beta_2-\beta_1)c]$. Therefore, for the above (opposite) condition, the producer price in direct online sales has a positive (negative) correlation with the retailer's price sensitivity coefficient for complementary goods, and the retailer's retail price has a negative (positive) correlation with its own price sensitivity.

7. The case of price war

An example of a manufacturer for the model above is Midea Group, an electrical appliance manufacturing company headquartered in Beijiao (Shunde District, Foshan County with a population of over 10 million by 2026, Guangdong Province, China). Midea has been listed on the Shenzhen Stock Exchange (founded in 1987) SZSE with the ticker 000333 since 2013 and has been a Fortune Global 500 company since 2016. Examples of retailers for the model above include Tmall (operated by Alibaba) and JD.com, Inc., the two largest online B2C retailers in China by transaction volume and revenue. JD.com is an e-commerce company headquartered in Beijing, the capital of China (population of over 23 million by 2026). JD.com is listed on the Hong Kong Stock Exchange (SEHK) with the ticker 9618.

On December 10, 2010, the founder of JD.com announced on his Weibo account that every book sold on JD.com would be 20% cheaper than that of competitors. Four days later, on December 14, 2010, rival firm Dangdang also began offering discounts to customers and announced its significant investment to provide discounts to customers. Therefore, JD.com launched a second promotion to sell books at a lower price than Dangdang and announced that it would provide coupons instead of price cuts to protect the interests of publishers. In 2011, JD.com offered its customers a 10% discount on books, while Dangdang sent promotional messages to its users. The sudden increase in orders not only caused network outages but also delayed the delivery of books.

In the field of e-commerce, price wars have become a common means for firms to compete for market share. Attention is paid to price wars on e-commerce platforms, their interaction models, and the ways in which firms adjust and optimize their pricing strategies in the context of dynamic competition. Based on the characteristics of price wars in e-commerce, definitions of static and dynamic game models, the regularities of price wars are analyzed, appropriate strategies of firms

are proposed, the impacts on market stability and long-term revenues of firms are illustrated, the outcomes of price wars on the long-term development of the industry are discussed, and appropriate recommendations, strategies, and plans for the future are proposed in order to achieve sustainable competitive advantages and maximize their market results in conditions of fierce price competition [16]. The spread of e-commerce is completely changing traditional retail, providing consumers with a more convenient and diverse shopping choice, but at the same time it leads to unprecedented market models and market competition: price wars have become a common means of competing for market share by many e-commerce platforms.

8. Conclusions

The pricing decision of a firm can be considered a strategic choice, the purpose of which is to maximize its own income. In such a competitive environment, the issue of developing an effective pricing strategy and maintaining a competitive advantage becomes the strategic basis of data-driven enterprise security. In the process of building and analyzing various models, it is better to understand the evolution of strategies in price wars and their long-term impacts on the market structure. E-commerce price wars and strategies for overcoming their consequences deserve attention. It is necessary to define the concept of price wars, develop appropriate data-based e-commerce models, discuss real-world examples, analyze the processes of strategy selection and interaction in e-commerce price wars, and also put forward proposals for optimal competitive strategies in e-commerce. Attention is paid to the issues of customer service levels, the coordination of supply and demand conflicts in supply chains, using common decision-making goals and unique relationships between complementary products. Based on game theory, it is possible to analyze the pricing strategies of complementary products in a three-tier two-channel supply chain, the relationship between pricing and service levels, and the optimization of performance in different channels. It is expected that the developed theoretical framework will be useful for developing theoretical recommendations for e-commerce enterprises to formulate more effective strategies in complex market competition and obtain long-term competitive and comparative advantages.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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