Pricing strategies for logistics robot sharing platforms

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Abstract: Sharing platforms play a key role in the development of the sharing economy. We consider a logistics robot sharing platform comprising logistics robot providers and customers that need to rent robots. We develop an analytical model to investigate pricing strategies of a sharing platform incorporating service response speed and additional services. After that, we examine the impact and value of the logistics robot sharing platform. We interestingly find that a high service response speed does not necessarily bring benefits to the platform. In addition, when customers are sensitive to additional services, despite the increased cost of providing additional services, the platform can still profit from them. Finally, we analytically compare the utility functions of customers to ascertain the impact of the service response speed of the platform with additional services.

Keywords: sharing economy; platform operations; logistics robot; service response speed; additional services

1. Introduction

1.1 Background and motivation

Today, in the digital era (Ivanov, Dolgui and Sokolov, 2019; Ivanov and Dolgui, 2020), platforms are a critical part of production and service systems. For example, sharing platforms can effectively match "supply and demand" online with the pool of suppliers and buyers. Thus, many sharing platforms have emerged in different industrial sectors in recent years. Typical examples include the service platforms in travel (e.g., Mobike and Uber), home leasing (e.g., Airbnb), luxury consumption (e.g., BagBorroworSteal and Tulerie), leftover food/eatables (e.g., Oasiseco), mobile charging (e.g., Energy Monster), crowdsourcing logistics (e.g., ele), capacity sharing (e.g., 3Dhubs and Machinery Link), and so on. They all revolutionaries the traditional lifestyle of people and extend the boundaries of traditional rental service operations.

Recently, logistics robots sharing (LRS) platforms, e.g., Earth-iot in China, have emerged to support the goal of elastic logistics (Choi 2020a). An LRS platform is a new type of sharing platform that helps integrate different logistics robot providers. In 2019, Earth-iot had more than 1,000 robots and an operating income exceeding 100 million yuan (Robotop, 2020). The robot rental service provided by the LRS platform is known as RaaS (robot as a service) (Yates, 2020). Through this service, customers order the required application software and hardware services from suppliers through the Internet, and pay according to the ordered service volume and service time. The Earth-iot platform plays an important role in integrating different robotics companies (e.g., Geek+, Hikvision, Megvii etc.) together. It also helps match and optimally allocate resources between users (such as Foxconn, Philips, ASE Group and so on) and robotics companies. Customers can rent logistics robots through the Earth-iot platform. In addition, the Earth-iot platform loads the self-developed Hi-box chip onto the robot to monitor the robot's real-time location and operational data, ensuring the proper functioning of the robots.

Robot-based artificial intelligence sparks a major revolution in supply chain and logistics management (Hahn, 2019; Winkelhaus and Grosse, 2019; Dolgui et al. 2019; Ivanov et al. 2020; Hashemi-Petroodi et al. 2020). Autonomous mobile robots can improve the efficiency and flexibility of production systems (Fragapane et al., 2020). Especially after COVID-19, the application of automation and robotics is one of the important means to improve the flexibility of the supply chain (Ivanov, 2021a; Ivanov, 2021b; Liu et al., 2021; Cui et al., 2021; Li et al., 2021). The existence of the LRS platform is necessary. First, the platform, as a linker, offers different types of logistics robots (such as production handling robots, warehousing and transportation robots, logistics sorting robots etc.) and standardized smart factory transformation solutions, from which customers can enjoy a one-stop service for logistics robot rentals. Compared with the customized services directly rented from logistics robot firms, platform renting greatly saves the time required to build a robot layout in the factory. Second, the main function of the LRS platform is to make available an industrial Internet cloud platform that provides visual services (We define it as "additional services" in the paper). Customers can intuitively see where the robot is, how it works, how much money can be saved, and how much efficiency can be improved through the cloud platform. Customers can also schedule and control the robots through the cloud platform (For example, on the Earth-iot platform, each logistics robot has a smart chip to collect operations data and the cloud platform enables customers to visually see the working status of the robot). Third, the advantage of renting through the platform is also that the platform has a service advantage. Because the platform provides a standardized logistics robot integration system, customers can get professional services and more capital flexible, convenient smart logistics solutions.

The use of the LRS platform to provide logistics robot rental service already exists in practice. However, there are several operational challenges that significantly hinder the widespread use of the LRS platform. For instance, since these two types of sharing exist in the logistics robot sharing industry. It is difficult to understand how valuable the platform is compared with direct leasing. More importantly, the platform's service responsiveness varies depending on the client's needs (customized or standardized service). We need to know whether the platform can benefit from adjusting the service response time, which is defined as the time that a customer takes to obtain a logistics robot through the platform, or inversely the service response speed. In addition, the additional services provided by the platform will increase the platform's operational costs but help customers reduce the cost of using the logistics robots. The platform manager needs to consider how to balance the service response speed and additional services to obtain the best benefit, and what pricing strategies the platform implement should when considering different service responsiveness.

Those factors have important impacts on the customer's experience. In terms of operations management, the following issues remain to be addressed:

(1) Compared the traditional logistics robot rental service, does the LRS platform bring benefit to the logistics robot firms and customers?

(2) What pricing strategy should the LRS platform adopt considering its own service responsiveness?

(3) How would the results of the above questions be affected if the platform provided additional services?

Noting the differences between the LRS platform and other sharing platforms, we aim to clarify the general operating rules of the sharing economy. We will examine the economic impact and value of LRS platform, and analyze the pricing decisions that consider the platform's provision of additional services and service responsiveness. We will also explore the LRS platform's decisions to understand the performance of the LRS platform. We consider two cases of the sharing model corresponding to the settings with and without the platform. We first discuss the impacts of the platform on the market demand, sharing price, and the platform's operations associate with considering LRS platform's pricing decisions. To capture the characteristics of the LRS platform, we then consider how the platform's additional services affect the logistics robot sharing market. Finally, we investigate what service response speed the platform should have when it considers to provide additional services. Analyzing the models, we derive results to address the various issues concerning logistics robot sharing and generate managerial insights from the analytical findings.

1.2 Contribution statements and paper arrangement

We make three key contributions about guiding the operation of the platform in this study. First, to the best of our knowledge, this paper is the first analytical study that examines the impact of platform operations on logistics robot sharing. The theoretical outcomes are all based on analysis with many novel and original findings. In particular, it highlights the impact brought by the service response speed and additional services provided by the LPR platform. Second, real-life sharing platforms often pursue responsive platform service. Despite such a common phenomenon in practice, our analysis shows that a high platform service response speed may not necessarily lead to an increase in business. This novel finding is contrary to that for the traditional platform operations. Third, our findings identify the conditions where the platform's provision of additional services can help increase profit. In addition, we find that the platform's ability to help customers reduce the cost of using logistics robots is key to its commercial success. Given that the logistics robot sharing via platform is an innovate practice in real world, the results of this study not only contribute to the relevant literature but also provide useful managerial insights to practitioners on how to use the LRS platform appropriately.

We organize the rest of the paper as follows: In Section 2, we give a brief review of the related literature to identify the research gap and position our work. In Section 3, we introduce the problem, formulate the model, and discuss the assumptions. In Section 4, we analyze the sharing model under different sharing strategies. In Section 5, we consider extensions of the model. In Section 6, we conduct further analyses. Finally, in Section 7, we conclude the paper and suggest topics for future research. All proofs are placed in Appendix A.

2. Literature Review

Our research belongs to the research stream concerning sharing platform operations, which relates to many concepts (Cai et al. 2020; Choi et al., 2020a; Choi et al., 2020b), such as price strategies, operations strategies for sharing platforms, and effects of the operation environment (including different types of customers and network externality). In addition, the platform has an impact on the operations of the supply chain, such as distribution channels (Tian and Jiang, 2017) and auctions (Bhargava et al. 2020). We review the recent pertinent studies in the following.

Sharing platform operations is a novel topic in operations management research. Researchers have studied platform operations in a wide range of industries. For example, He and Shen (2015) simulated taxi services based on the e-hailing platform and investigated the pricing and compensation strategies (He et al. 2018; Guan et al., 2020). Bimpikis et al. (2019) and Wu et al. (2019) explored the spatial price of the ride-sharing platform. Guo et al. (2021) studied demand forecasting of car-hailing platform based on multidimensional. Sun et al. (2021) investigated the logistics capacity sharing platforms. In addition, Wang et al. (2016), Cohen and Zhang (2017), Zhong et al. (2018), Sun et al. (2020a), and Wu et al. (2020) studied ride-sharing platform operations under different scenarios. Yuan and Shen (2019), and Choi and He (2019) considered collaborative consumption of fashion products through a sharing platform. Asian et al. (2019), Choi et al. (2019), and Harvey et al. (2019) explored the sustainability and value of the food sharing platform. In addition, Aloui and Jebsi (2016), Jiang and Tian (2018), Benjaafar et al. (2018) discussed the economic implications of product sharing through platforms, especially capacity sharing in the manufactory industry. Recently, Qin et al. (2019), similar to Kung and Zhong (2017), studied the logistics service sharing problem on a sharing platform. Choi (2020b) explored the value of elastic logistics for various online platforms. He quantified the values of the respective platforms. Sun et al. (2020a) and Sun et al. (2020b) investigated the price strategies of 3D printing platforms. Pan et al. (2020) investigated how a peer-to-peer (P2P) lending platform could help recognize 'bad' applicants. Chiu and Chuang (2021) investigated sharing strategies of sharing kitchen platforms. It is evident from the above discussion that sharing platform operations in different industries is of importance to the sharing economy. Based on the previous research, we investigate the sharing platform operations in a particular industry, i.e., logistics robot sharing.

The pricing strategies for sharing platforms have attracted growing research attention due to the importance of sharing platform operations (Weyl, 2010). Focusing on the pricing strategies for a platform considering network externality, Kung and Zhong (2017) studied how the platform charges the participants. Wang et al. (2016) considered the pricing strategies for a taxi-customer matching platform and found that the pricing strategies affect the taxi market performance. Lin and Zhou (2019) explored the pricing strategies for a platform with self-scheduling providers. They found that the surging price strategy is not always perfect. Similarly, Cachon et al. (2017) found that the surging price strategy is not optimal. Xue et al. (2019) investigated the pricing problems of a monopolistic and a duopolistic platform. They found that the optimal price is proportional to the service cost and quality in both markets. Liu et al. (2019) investigated the pricing problem of a platform with a threshold for participants. They found that the threshold affects the pricing decisions in the low-demand condition rather than the high-demand condition. Based on mean-risk theory, Choi et al. (2020) found that the risk attitudes of the customers would affect the pricing decision of a platform. Cheng et al. (2021) supposed that data-driven decision platform supports the development of circular economy. While also investigating the pricing strategies for a sharing platform, different from the above studies, we explore customers' utility of the sharing price that takes customers' utility into consideration.

In addition, some researchers consider the operations strategies for sharing platforms. The platform in the sharing economy is an open multilateral platform that can help firms achieve sustainable development (Meng et al. 2019). A stream of research focuses on how service quality affects the operations of sharing platforms. For example, Halaburda et al. (2018) showed that restricted customers' choice may increase the service response speed and allows the platform to charge a high price. Xue et al. (2019) explored how service quality can improve the profit of the sharing platform. The results show that improving service quality is not necessarily a good strategy because the cost of investing in enhancing service quality is high. Wen and Siqin (2019) considered that the service (product) quality is related to cost. Besides, Liu et al. (2019) claimed that a threshold for participants to join a sharing platform may increase the profit of the platform. Zhou et al. (2019) studied how to choose a contract for a sharing platform with self-scheduling capacity. Cai et al. (2020) built platform-supported supply chain models based on blockchain for supply chain coordination. Zhan et al. studied price competition of blockchain-platform-based supply chain. Guda and Subramanian (2019) studied how the platform motivates workers to participate in platform services. They showed that surge pricing can to some extent motivate workers to join the platform and serve consumers.

Moreover, there is research on the operations of sharing platforms facing different types of customers and environment. For instance, Bai et al. (2019) discussed the impact of impatient customers joining a sharing platform. They found that the waiting cost is not monotonically increasing with the price of the platform. Taylor (2018) proposed that more waiting time would reduce customers' utility and the service price of the platform. Facing risk-sensitive customers, Choi et al. (2020) suggested that different risk attitudes are essential for a platform to set the optimal pricing strategies. Considering the members of a sharing platform are strategic customers, Yuan and Shen (2019) found that the platform should increase the cost of product returns to combat customers' illegal behavior. Kim et al. (2017) studied a sharing platform with multi-homing agents and found that the platform is hard to produce a competitive bottleneck. Kung and Zhong (2017) formulated a profit model of a sharing platform by considering that network externality that exists in platform's participants. Wang et al. (2019) investigated the influence of government regulations on a sharing platform considering network externality. More importantly, Chu and Manchanda (2016) found that direct network effects have little effect on the growth of the platform and cross-network effects at both ends of the platform are asymmetrical.

Different from the above research on sharing platform operations, we examine the impact of platform operations, which is a common issue in sharing platform management, where the platform can provide additional services. Moreover, to make a thorough inquiry into the optimal decisions of the platform, we consider the platform service response speed in order to gain insights totally different from those derived from the above research.

3. Problem Description

Our model will be formulated based on the operation practice in Earth-iot, a famous logistics robot sharing platform in China. Earth-iot provides a variety of logistics robots including forklift AGVs (Automated Guided Vehicles), material handling AGVs, and sorting AGVs for customers to rent. We consider the RaaS mode as shown in Figure 1, where the platform providing the rental service connects the logistics robot providers and users. For each logistics robot provider, it should pay service fees to the platform. After a customer makes a sharing requirement, the platform will meet the customer's requirement within a certain period of time, which is called the service response speed of the platform. In addition, Earth-iot platform provides additional services, e.g., visual operations, for customers.

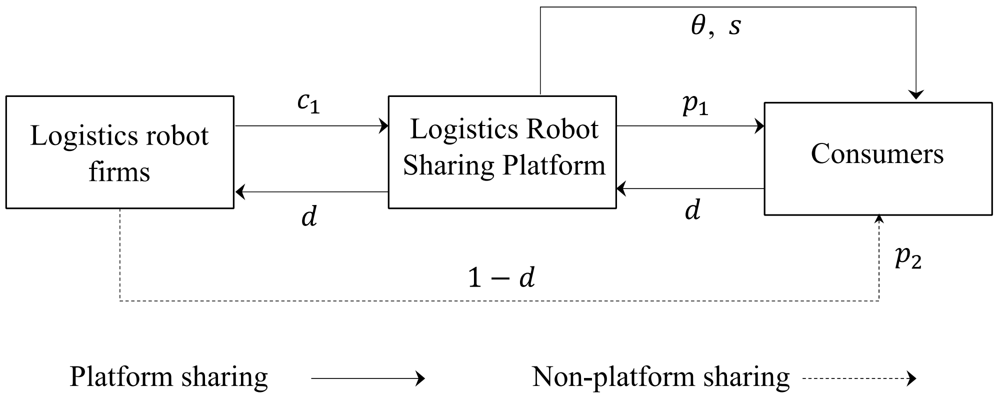


Figure 1. The logistics robot sharing platform operations.

The additional services can help customers reduce the cost of using the logistics robots. As a result, these services have important impacts on the customers' experience, as well as on the platform's demand. Since the additional services will increase the platform's operational costs, the platform manager needs to consider how to balance the service response speed and additional services to obtain the best benefit.

Specifically, there is a unique logistics robot sharing market and the sharing demand via the platform is d, so the sharing demand without the platform is $1-d$ (Sun et al., 2020; Chai et al., 2020). We consider a monopolistic platform that provides the logistics robot sharing service whereby the participants comprise two groups in the market, namely logistics robot owners (logistics robot firms) and logistics robot users (customers). The platform integrates logistics robot firms with a service response speed θ to match the supply and demand for logistics robots. Moreover, the platform provides participants with additional services at quality level s. The customers' utility of the additional services is larger than that without it. The customers send orders through the platform and ask the platform to provide robots for them. The logistics robot firms can share their products through the platform at price p_1. In order to determine the value of the platform, we compare it with the situation without sharing through the platform where the sharing price is p_2. Not that p_i $(i = 1,2)$ is not the sharing price per robot, but the price that logistics robotics firms charge customers for each transaction. This price includes not only a number of robots (d or $1 - d$ robots), but also a smart warehouse solution provided by logistics robotics firms. We consider c_1 refers to the service fees that the logistics robot firms pay to the platform, c_2 refers to the search cost of finding customers for the logistics robotics company.

In addition, we assume that the customers are rational that make decisions to maximize their utility. We summarize in Table C (see Appendix C) the notation used throughout the paper.

4. The Analytical Model

4.1 Logistics robot firms' and the LRS platform's decisions

In this section we first develop the logistics robot firm's profit models of sharing with and without the LRS platform, respectively, and then develop platform's profit model to explore its optimal decisions. We analyze the optimal pricing strategies for the two cases, and then evaluate the impact of the LRS platform. Next, we formulate the optimal strategies for the LRS platform, which show how the platform should recruit participants.

We denote the maximum utility that customers can obtain as u ($u > 0$) and the sharing price charged to the logistics robot firms as p_i ($i = 1, 2$, where $i = 1$ represents the case where the logistics robot firms share their products through the platform; $i = 2$ represent the case where the platform is not used). If a logistics robot firm joins the LRS platform, its utility is determined by the service response speed θ ($\theta > 0$). $t > 0$ refers to unit cost of using logistics robots. We assume that there is a unit number of logistics robots in the market. A fraction of logistics robots d ($d \leq 1$) will be shared through the platform, so the other fraction of logistics robots $(1 - d)$ will be shared directly without the involvement of the platform. The utility of customers with the LRS platform is determined by the service response speed. The use cost and rental price of logistics robots have a negative impact on customer utility. Thus, the utility of customers with the LRS platform and the utility of customers without the LRS platform are, respectively, as follows:

$$U_p = \theta(u - p_1 - td), \tag{1}$$

$$U_d = u - p_2 - t(1 - d). \tag{2}$$

Equation (1) and Equation (2) indicate that the representative consumer utility is linearly dependent on sharing price, unit cost of using logistics robots and demand. Plus, the utility perceived by consumers who share robots through the platform is critically determined by the waiting time after placing orders on the LRS platform, i.e. service response speed of the platform. Equation (1) also implies that the utility increases in service response speed while decreases in total cost of using logistics robots and sharing price. Similar specification of demand functions can be found in Chai et al. (2020), Li et al. (2020), Sun et al. (2020), Xue et al. (2018), Chen et al. (2017), Kung and Zhong (2017), etc.

The demand for logistics robots is determined by the utility of the customers. We consider that customers will use logistics robots when their utilities are positive, i.e. $U_p > 0$ and $U_d > 0$. Then letting $U_p = U_d$ yields

$$d = \frac{u(\theta-1)-\theta p_1+p_2+t}{t(\theta+1)}. \tag{3}$$

We then obtain the profit function of the logistics robot firms with and without the LRS platform, respectively, as follows:

$$\pi_p = (p_1 - c_1)d, \tag{4}$$

$$\pi_d = (p_2 - c_2)(1 - d). \tag{5}$$

It is easy to find that π_p and π_d is strictly concave functions of p_1 and p_2, respectively. Differentiating (4) with respect to p_1 once and differentiating (5) once with respect to p_2, and solving the first-order conditions, we get the optimal sharing prices of those two sharing cases, respectively, as follows:

$$p_1 = \frac{u(\theta-1)+p_2+t+\theta c_1}{2\theta}, \tag{6}$$

$$p_2 = \frac{\theta(t-u+p_1)+u+c_2}{2}. \tag{7}$$

Obviously, it is easy to derive the results of the optimal prices of two sharing cases ${p_1}^*(c_1)$ and ${p_2}^*(c_1)$ by combining (6) and (7) as follows:

$${p_1}^*(c_1) = \frac{\theta(2c_1+t+u)+(2t+c_2-u)}{3\theta}, \tag{8}$$

$${p_2}^*(c_1) = \frac{\theta(2t+c_1-u)+(t+2c_2+u)}{3}. \tag{9}$$

Substituting (8) and (9) into (3) yields the demand function under the optimal sharing price, as follows:

$$d^*(c_1) = \frac{\theta(u-c_1+t)+(2t-u+c_2)}{3t(\theta+1)}. \quad (10)$$

Then, we consider platform's decisions. The LRS platform incurs an operation cost m and charges logistics robot firms service fees c_1. The LRS platform's profit is as follows:

$$\pi_{LRSP}(c_1) = (c_1 - m)d^*(c_1). \quad (11)$$

Differentiating (11) with respect to c_1 twice yields $\frac{\partial^2 \pi_{LSPP}}{\partial {c_1}^2} = -\frac{2\theta}{3t(1+\theta)} < 0$. So $\pi_{LSPP}(c_1)$ is a strictly concave function of c_1 and the optimal c_1 can be fund by solving the first-order condition as follows:

$$c_1{}^* = \frac{\theta(m+t+u)+(2t-u+c_2)}{2\theta}. \quad (12)$$

Putting (12) into (8), (9), and (10) yields the optimal sharing prices and demand as follows:

$$p_1{}^* = \frac{\theta(m+2u+2t)+2(2t+c_2-u)}{3\theta}, \quad (13)$$

$$p_2{}^* = \frac{\theta(m-u+5t)+(4t+5c_2+u)}{6}, \quad (14)$$

$$d^* = \frac{\theta(t+u-m)+(2t+c_2-u)}{3t(\theta+1)}. \quad (15)$$

Putting (12), (13), and (15) into (4), putting (14), and (15) into (5), putting (12) and (15) into (11), respectively, yield the logistics robot firm's expected profit with and without LRS platform, and the LRS platform's expected profit as follows:

$$\pi_p{}^* = \frac{(2t-u-m\theta+t\theta+u\theta+c_2)^2}{36t\theta+36t\theta^2}, \quad (16)$$

$$\pi_d{}^* = \frac{(4t+u+m\theta+5t\theta-u\theta-c_2)^2}{36t+36t\theta}, \tag{17}$$

$$\pi_{LRSP}{}^* = \frac{(2t-u-m\theta+t\theta+u\theta+c_2)^2}{12t\theta+12t\theta^2}. \tag{18}$$

By analyzing the equilibrium solutions for two sharing cases and the LRS platform, we derive the logistics robot firm' and the LRS platform's optimal prices and optimal expected profits. The analytical results are summarized in Table B1. We are surprised to find that whether sharing logistics robots through the LRS platform, the optimal sharing price and optimal expected profits depend on the service response speed θ, which is count-intuitive and interesting. It is because the existence of the LRS platform has a significant impact on the logistics robots sharing market.

To generate more insights, we perform sensitivity analyses of the optimal decisions to the key parameters in Section 4.2.

4.2 Analytical sensitivity analyses

Sharing through the LRS platform will definitely affect the logistics robots leasing market. In this subsection, we examine the impact of the LRS platform by performing a partial-derivative based sensitivity analyses of the equilibrium results. The sensitivity analyses for key parameters of basic models are summarized in Table B1.

For the LRS platforms' decisions and demand, we have the following results:

Proposition 1:

(1) The demand quantity of the LRS platform increases with the service response speed when $t > 2u - (m + c_2)$ *and decreases with the service response speed when* $t < 2u - (m + c_2)$.

(2) The service fees charged by the platform increases with the service response speed when $t < \frac{u-c_2}{2}$ *and decreases with the service response speed when* $t > \frac{u-c_2}{2}$.

Proposition 1 shows the relationship between the demand for logistics robots through the platform and the service response speed of the LRS platform. The impact of service response speed on the platform is non-monotonic. The use cost of logistics robots plays an important role in the operation of the platform. If the use cost of robots is high, customers tend to share through the platform because the platform can help customers reduce costs by providing services. When the unit cost of using logistics robots is low, regardless of the service response speed, customers tend to rent robots directly from the logistics robot firms. This result suggests that a high response speed of the platform may not necessarily lead to an increase in business.

Because the LRS platform (like the Earth-iot) is not a just-in-time service platform, it takes time for logistics robots to be laid out to a customer's factory or warehouse. As a result, the platform's quick service response is not a decisive factor in increasing demand. Proposition 1 suggests that customers willing to rent robots through the Earth-iot platform are not time sensitive, but are sensitive to the cost of using logistics robots.

In addition, we find that the LRS platform that provide high response speed can charge high service fees if customers' cost to use logistics robots is low. On the country, if customers' cost of using logistics robots is high, high platform's response speed leads to platform charge low service fee. In other words, customers' cost of using logistics robots affects the LRS platform's pricing decision-making. This is because if customers are familiar with the use of logistics robots (the cost of using the robot is low), then the help brought by the platform is limited, and the platform's fees will be lower.

To examine how the pricing strategy affects the platform along with the service response speed, we perform a partial-derivative based sensitivity analysis of the optimal price strategies for different sharing cases.

For sharing prices, we summarize the result in Proposition 2.

Proposition 2:

(1) The sharing price of the LRS platform increases with the service response speed when $t < \frac{u-c_2}{2}$ *and decreases with the service response speed when* $t > \frac{u-c_2}{2}$.

(2) The sharing price without the LRS platform increases with the service response speed when $t > \frac{u-m}{5}$ *and decreases with the service response speed when* $t < \frac{u-m}{5}$.

Proposition 2 shows the relationship between the sharing price and service response speed of the LRS platform. To a certain extent, a high service response speed means high service quality of the platform. An increase in the service response speed does not necessarily cause the platform to increase the sharing price, which means that even if the platform service quality is high, it will not blindly seek a high price. When the cost of using logistics robots is high, the platform adopts the low-price strategy to attract customers. This finding suggests that a high service response speed does not necessarily attract customers and logistics robot firms to join the platform, as attracting participants to join the platform also depends on the cost of using logistics robots.

In fact, the platform will find ways to help customers reduce the cost of using their logistics robots. For example, the Earth-iot will provide additional services to solve the obstacles that customers encounter in using the robots (we discuss the *additional services* in the extended model).

4.3 Value of the LRS platform

Whether the logistics robot firms and consumers use the platform is essential to the platform's gaining of more profit. We study the difference between the optimal profits of the two cases with and without the platform. Evidently, it is related to the service response speed θ as well. So, we consider

$$\Delta\pi = {\pi_p}^* - {\pi_d}^*. \qquad (19)$$

Equating (19) to zero yields the following result.

Proposition 3: *If* $\theta > \frac{t+u+c_2}{u-m-2t}$, *we have* $\Delta\pi > 0$*; if* $\theta < \frac{t+u+c_2}{u-m-2t}$, *we have* $\Delta\pi < 0$*; and if* $\theta = \frac{t+u+c_2}{u-m-2t}$, *we have* $\Delta\pi = 0$.

Proposition 3 indicates that the existence of the LRS platform is not necessarily beneficial to the logistics robot sharing market. The advantage of the platform is related to the service response speed of the platform. The value of the platform also depends on the customer's cost of using the logistics robot. Observe that the service response speed is related to the cost of the logistics robot firms. An increase in the cost will stimulate the platform to improve the service response speed.

5. Extensions

To check robustness of the results from the basic model as well as to examine how the performance of robot sharing with and without the LRS platform considering the additional services. We extend the model to consider both service responsiveness and additional services. The platform provides participants with additional services at quality level s. Thus, the utility of customers with and without additional services of the LRS platform are as follows:

$$U_p^s = \theta(u - p_1^s - td^s) + \alpha s, \tag{20}$$

$$U_d^s = u - p_2^s - t(1 - d^s). \tag{21}$$

We denote s as the additional services provided by the LRS platform; α as customers' sensitive coefficients of service, which plays a crucial role when the platform provides additional services.

Similar to the analysis of the basic model, we obtain the alternative demand function by making $U_p^s = U_d^s > 0$ as follow:

$$d^s = \frac{u(\theta-1)-\theta p_1^s+p_2^s+\alpha s+t}{t(\theta+1)}. \tag{22}$$

Then, we obtain the extended profit function of logistics robot firms with and without the LRS platform, respectively, as follows:

$$\pi_p^s = (p_1^s - c_1^s)d^s, \tag{23}$$

$$\pi_d^s = (p_2^s - c_2)(1 - d^s). \tag{24}$$

Differentiating (23) with respect to p_1^s once and differentiating (24) once with respect to p_2^s, and solving the equation consisting of first-order conditions, we derive the optimal sharing prices of those two sharing cases with additional services, respectively, as follows:

$$p_1^{s*}(c_1^s) = \frac{\theta(2c_1^s+t+u)+(2t+c_2-u)+s\alpha}{3\theta}, \tag{25}$$

$$p_2^{s*}(c_1^s) = \frac{\theta(2t-u+c_1^s)+(t+u+2c_2)-s\alpha}{3}. \tag{26}$$

Substituting (25) and (26) into (22) yields

$$d^{s*}(c_1^s) = \frac{\theta(t+u-c_1^s)+(2t-u+c_2)+\alpha s}{3t(\theta+1)}. \tag{27}$$

Then, we consider platform's decisions with additional services. Besides the operation cost m, the LRS platform is required an investment which is denoted by $\Phi(s)$ to provide additional services. We follow the literature to set $\Phi(s)$ is and quadratic function denoted as $\Phi(s) = \frac{1}{2}ks^2$ (Liu et al., 2021; Choi and Xu, 2021; Wen and Siqin, 2021, Guo et al., 2020; Jiang et al., 2016), where $k > 0$ is a cost coefficient. So the LRS platform's profit is as follows:

$$\pi_{LRSP}^{s}(c_1^s,) = (c_1^s - m)d^{s*}(c_1^s) - \frac{1}{2}ks^2. \tag{28}$$

Differentiating (28) with respect to c_1^s twice yields $\frac{\partial^2 \pi_{LRSP}^s}{\partial {c_1}^2} = -\frac{2\theta}{3t(1+\theta)} < 0$. So $\pi_{LRSP}^s(c_1^s)$ is a strictly concave function of c_1^s and the optimal c_1^s can be fund by solving the first-order condition as follows:

$$c_1^{s*} = \frac{\theta(m+t+u)+(2t-u+c_2)+s\alpha}{2\theta}. \tag{29}$$

Putting (29) into (25), (26), and (27) yields the optimal sharing prices and demand under these extended modes as follows:

$$p_1^{s*} = \frac{\theta(m+2u+2t)+2(t+c_2-u)+2s\alpha}{3\theta}, \tag{30}$$

$$p_2^{s*} = \frac{\theta(m-u+5t)+(4t+5c_2+u)-s\alpha}{6}, \tag{31}$$

$$d^{s*} = \frac{\theta(t-m+u)+(c_2+2t-u)+s\alpha}{6t+6t\theta}. \tag{32}$$

Putting (29), (30), and (32) into (23); putting (31) and (32) into (24); putting (29) and (32) into (28), respectively, yield the logistics robot firm's expected profit with and without the LRS platform, and the LRS platform's expected profit as follows:

$$\pi_p^{s*} = \frac{[2t-u+s\alpha+c_2+\theta(t-m+u)]^2}{36t\theta+36t\theta^2}, \tag{33}$$

$$\pi_d^{S*} = \frac{[4t+u-s\alpha-c_2+\theta(m+5t-u)]^2}{36t+36t\theta}, \tag{34}$$

$$\pi_{LRSP}^{S*} = \frac{1}{2}\left[\frac{(2t-u+s\alpha+\theta(t-m+u)+c_2)^2}{6t\theta+6t\theta^2} - ks^2\right]. \tag{35}$$

Next, we conduct sensitivity analyses towards the key parameters in the above extended models to gain more insights. The sensitivity analyses for key parameters of extended models is summarized in Table B2. The results showed in Table B2 are derived from checking the first-order derivatives of the optimal solution.

For the LRS platform's decisions and demand under the condition considering both service responsiveness and additional services, we have the following results:

Proposition 4: *Under the condition considering both service responsiveness and additional services:*

(1) The demand of the platform increases with the service response speed when $t < 2u - (m + c_2) - s\alpha$ and decreases with the service response speed when $t > 2u - (m + c_2) - s\alpha$.

(2) The demand of the platform also increases with the level of additional service.

(3) The service fees charged by the platform increases with the service response speed when $t < \frac{u-c_2-s\alpha}{2}$ and decreases with the service response speed when $t > \frac{u-c_2-s\alpha}{2}$.

(4) The service fees charged by the platform also increase with the level additional services.

Proposition 4 demonstrates that the cost of using a logistics robot has a critical impact on the LRS platform, which is consistent with the findings derived in the basic model. Specifically, when the cost of using logistics robots is low, higher service responsiveness of the LRS platform leads to an increase in demand. In addition, additional services will lead to increased demand for the platform. This is because the LSR platform provides additional services to customers, which is equivalent to helping customers reduce the cost of using logistics robots.

In addition, we also find that providing additional services result in higher service fees charged by the LRS platform due to the fact that additional services lead to higher costs for the platform.

For sharing prices under the condition considering both service responsiveness and additional services, we have the following results:

Proposition 5: *Under the condition considering both service responsiveness and additional services:*

(1) The sharing price of the LRS platform increases with the service response speed when $t < \frac{u-c_2-s\alpha}{2}$ and decreases with the service response speed when $t > \frac{u-c_2-s\alpha}{2}$.

(2) The sharing price of the LRS platform also increase with the level additional services.

(3) The sharing price without the LRS platform increases with the service response speed when $t > \frac{u-m}{5}$ and decreases with the service response speed when $t < \frac{u-m}{5}$.

(4) The sharing price without the LRS platform also decreases with the level additional services.

For the effect of the platform's service responsiveness on the platform's optimal pricing decision, Proposition 5 yields results consistent with the one in the basic model. Moreover, the additional services offered by the platform result in the platform raising the price of sharing, but causing logistics robotics companies that do not join the platform to lower the sharing price. This finding suggests that the platform's efforts have intensified price competition in the logistics robot sharing market. Since the platform absorbed a large amount of market resources for logistics robots and had strong pricing power, logistics robot companies that have not joined the platform need to adopt a low-price strategy to attract customer service in order to survive.

6. Further Analyses

6.1 Endogenous additional services

We have explored the impact of additional services on decisions of platform and logistics robot firms. We are also interested in how the platform decide its additional services level. So in this sub-section, we regard s as an endogenous variable to study platform's decision-making. In fact, the additional services level of LRS platform could be an operational decision because these services help platform attract more participants.

For example, Earth-iot LRS platform decide to provide centralized cloud platform to help customers schedule and control robots in real time, which means that the Earth-iot LRS platform provides high quality additional services to customers. In addition to the usual robot rental services, the platform also helps customers to analyze the operational efficiency of their robots and optimize their service capabilities. These additional services are attractive to customers.

Accordingly, the LRS platform's profit is as follows:

$$\pi_{LRSP}^{ss}(c_1^{ss}, s) = (c_1^{ss} - m)d^{ss*}(c_1^{ss}, s) - \frac{1}{2}ks^2. \tag{36}$$

The hessian matrix π_{LRSP}^{ss} with respect to c_1^{ss} and s is $det\, H[c_1^{ss}, s] = \begin{vmatrix} -\frac{2\theta}{3t+3t\theta} & \frac{\alpha}{3t+3t\theta} \\ \frac{\alpha}{3t(1+\theta)} & -k \end{vmatrix} = -\frac{\alpha^2-6kt\theta(1+\theta)}{9t^2(1+\theta)^2}$. To vailed the analysis, we consider when $\alpha^2 < 6kt\theta(1+\theta)$, $detH[c_1^{ss}, s] > 0$, so $\pi_{LRSP}^{ss}(c_1^{ss}, s)$ is a strictly concave function and its maximum value exits.

Then, we have

$$c_1^{ss*} = \frac{6kt^2 - m\alpha^2 + 3k\left[t(c_2-u)+\theta\left(mt+3t^2+tc_2\right)+t\theta^2(m+t+u)\right]}{6kt\theta(1+\theta)-\alpha^2}, \tag{37}$$

$$s^* = \frac{\alpha[(2t-u+c_2)+\theta(t+u-m)]}{6kt\theta(1+\theta)-\alpha^2}. \tag{38}$$

Putting (37) and (38) into (27) yields

$$d^{ss*} = \frac{k\theta[(2t-u+c_2)+\theta(t+u-m)]}{6kt\theta(1+\theta)-\alpha^2}. \tag{39}$$

Putting (37) and (38) into (25) and (26) yields

$$p_1^{ss*} = \frac{2kt(1+\theta)[\theta(m+2u+2t)-2u+4t]+4kt(1+\theta)c_2-m\alpha^2}{6kt\theta(1+\theta)-\alpha^2}, \tag{40}$$

$$p_2^{ss*} = \frac{t(1+\theta)\left[k\theta(4t+u+\theta(m+5t-u))-\alpha^2\right]+[\alpha^2-5kt\theta(1+\theta)]c_2}{6kt\theta(1+\theta)-\alpha^2}. \tag{41}$$

Then, the logistics robot firm's expected profit with and without the LRS platform, and the LRS platform's expected profit are as follows:

$$\pi_p^{ss*} = \frac{k^2t\theta(1+\theta)[\theta(t-m+u)+2t+c_2-u]^2}{(\alpha^2-6kt\theta(1+\theta))^2}, \tag{42}$$

$$\pi_d^{ss*} = \frac{t(1+\theta)\left[\alpha^2-k\theta\left(4t+u+\theta(m+5t-u)\right)+k\theta c_2\right]^2}{(\alpha^2-6kt\theta(1+\theta))^2}, \tag{43}$$

$$\pi_{LRSP}^{ss*} = \frac{k[\theta(t-m+u)+2t+c_2-u]^2}{2[6kt\theta(1+\theta)-\alpha^2]}. \tag{44}$$

By the analysis above, we derive optimal solutions of the LRS platform and logistics robot firms under the model of endogenous additional services. Next, we conduct sensitivity analyses towards the key parameters in the above extended models to gain more insights. The sensitivity analyses for key parameters of extended models is summarized in Table B3. The results showed in Table B3 are derived from checking the first-order derivatives of the optimal solution.

For the LRS platform's decisions and demand under the condition considering endogenous additional services, we have the following results:

Proposition 6. *Under the condition considering endogenous additional services:*

(1) The demand of the platform increases with the service response speed when $\alpha^2 < \frac{6kt\theta^2(2u-t-m-c_2)}{2\theta(t+u-m)+(2t+c_2-u)}$ *and decreases with the service response speed when* $\alpha^2 > \frac{6kt\theta^2(2u-t-m-c_2)}{2\theta(t+u-m)+(2t+c_2-u)}$.

(2) The service fees charged by the platform increases with the service response speed when $\alpha^2 < \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$ *and decreases with the service response speed when* $\alpha^2 > \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$.

(3) The additional services level of the platform increases with service response speed when $\alpha^2 < \frac{6kt[\theta^2(t-m+u)+(2t-u+c_2)(2\theta+1)]}{m-t-u}$ *and decreases with the service response speed when* $\alpha^2 > \frac{6kt[\theta^2(t-m+u)+(2t-u+c_2)(2\theta+1)]}{m-t-u}$.

Proposition 6 show the impact of service response speed on the LRS platform. We find that customers' sensitivity to additional services plays a key role in these effects. If customers are sluggish to additional services (a lower α), a higher θ leads to a lower d^{ss*}, c_1^{ss*} and s^*, which means that there is no need for the platform to provide high level of additional services. These results are reasonable because customers with low sensitivity to additional services do not have an urgent need for enjoy additional services, the LRS platform should provide basic robot sharing services to save operating cost.

In fact, low additional services are acceptable when θ is small enough because a low service response speed may result in the platform losing its existing value. If customers are sensitivity to additional services (a higher α), the Earth-iot LRS platform needs to lay out the logistics robots in the customers' factories or warehouses as quickly as possible.

For sharing prices under the condition considering endogenous additional services, we have the following results:

Proposition 7. *Under the condition considering endogenous additional services:*

(1) The sharing price of the LRS platform increases with the service response speed when $\alpha^2 < \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$ and decreases with the service response speed when $\alpha^2 > \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$.

(2) The sharing price without the LRS platform increases with the service response speed when $\alpha^2 < \frac{(u-2t+c_2)+3\theta^2(3t-u+m)+2\theta(3t+m+c_2)}{6kt\theta^2(1+\theta)^2(u-m-5t)}$ and decreases with the service response speed when $\alpha^2 > \frac{(u-2t+c_2)+3\theta^2(3t-u+m)+2\theta(3t+m+c_2)}{6kt\theta^2(1+\theta)^2(u-m-5t)}$.

Proposition 7 show the impact of service response speed on the sharing prices. We find that the service responsiveness of the platform has a non-monotonic effect on sharing prices, regardless of whether the logistics robotics firms use the platform or not.

In practice, additional services including collecting the robot working data, analyzing the working status of the robot, and keeping track of how much efficiency has improved through using logistics robots. If consumers are more sensitivity to additional services, the platform can attract more customers, and further, it is easier for logistics robot firms to share their robots, Thus, with a high α, the speed of service response becomes less important, a higher θ will not cause high sharing price.

Note that in Subsection 6.1, additional services level s is seen as a decision variable, so customers' sensitivity α to s is more important, and in Propositions 6 and 7, we derive above important insights about the role of α plays in logistics robot sharing market.

6.2 Consideration of service response speed

If the platform wants to attract more users to join in, it must guarantee that customers gain more utilities than sharing without the platform, i.e., $U_p^s > U_d$. Moreover, when additional services are provided by the platform, the customers will gain more utility than joining the platform without additional services, i.e., $U_p^s > U_p$. The customers seek to attain their maximum utility in the process of sharing, so we have $U_p^s > U_p \geq U_d$.

In order to compare the utility of the logistics robot firms gained when deciding the sharing decision, we need to derive critical points for different cases of sharing with the platform. Letting $U_p^s = U_p = U_d = 0$ yields

$$u_1 = p_1 + td, \tag{45}$$

$$u_2 = p_2 + t(1-d), \tag{46}$$

$$u_3 = \frac{\theta(p_2^s + td) - \alpha_2 s}{\theta}. \tag{47}$$

where u_1, u_2, and u_3 are the maximum utility that the customers in the cases of sharing via the platform, no platform sharing, and sharing via the platform with additional services, respectively.

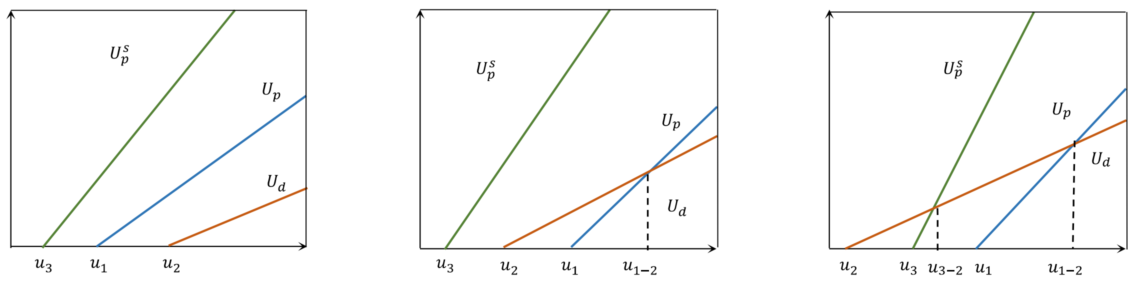
In addition, we need to consider two other critical points arising from $U_p = U_d$ and $U_p^s = U_d$, which yield $u_{1-2} = \frac{\theta p_1 - p_2 + t[d(\theta+1)-1]}{(\theta-1)}$ and $u_{3-2} = \frac{\theta p_2^s - p_2 + t[d(\theta+1)-1] - \alpha_2 s}{(\theta-1)}$, where u_{1-2} represents that the customers will gain the same maximum utility when joining the platform without the additional services, u_{3-2} represents that the customers will gain the same maximum utility when joining the platform with the additional services. Note that the case where $U_p = U_p^s$ need not be considered.

From the above analysis, to guarantee $U_p^s > U_p \geq U_d$, we investigate the service response speed under three scenarios as shown in Figures 2(a)-2(c):

Scenario 1: $u_3 < u_1 < u_2$

Scenario 2: $u_3 < u_2 < u_1 < u_{1-2}$

Scenario 3: $u_2 < u_3 < u_{3-2} < u_1 < u_{1-2}$



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

Figure 2. Three scenarios of different utility functions.

Solving the inequality under scenarios 1, 2, and 3, we derive the results which are summarized in Proposition 7.

Proposition 8: *If the platform provides certain quality of additional services, the service response speed must satisfy the condition* $0 < \theta < \frac{\alpha_2 s}{p_2^s - p_1}$.

We have shown in Proposition 1 that the LRS platform does not necessarily benefit from a high service response speed. Moreover, we derive in Proposition 7 the maximum service response speed of the platform. Specifically, an increase in additional services will lead to an increase in the service response speed. So Proposition 7 implies that the platform can make up for the loss caused by a low service response speed through improving the additional services quality. In addition, the sensitivity of the logistics robot firms to service also has an impact on the service response speed. To some extent, a high service response speed also means that the platform service quality is high.

7. Conclusions

7.1 Concluding remarks

The differentiation and specialization levels of platform services are key factors in research issues concerning the use of idle resources on the sharing platform and the innovation of business models, which is of great significance to the operation of sharing platforms. The logistics robot sharing platform has emerged recently. The sharing of robots on a platform is different from the sharing of other products or services in that the former often provides additional services. Such services are based on big data, IoT, and other technologies to collect logistics robot operations data and them it with the platform users through the cloud. We consider the impacts of such additional services on the platform's operations.

In conclusion, we obtain the following major findings:

(1) The demand for the platform is affected by the non-monotonic service response speed and is related to the cost of using the logistics robot. A high response speed does not

necessarily make the platform attractive to customers. Only when the use cost of the robot is high can a high response speed benefit the platform.

(2) The sharing price is affected by the non-monotonic service response speed and is related to the cost of using the logistics robot. The platform will not increase the sharing price due to improvement in the high service response speed when the cost of using the logistics robot for consumers is high.

(3) The platform need not show its value by increasing the service response speed, but should consider the customer's robot use cost.

(4) Additional services offered by LRS platform would lead to increased demand and higher sharing price, but would also lead to greater price competition in the logistics robotics sharing market.

(5) If the customers are sensitive to additional services, the platform should increase its service level and charge high service fees. In this case, the platform can compensate for the loss caused by low service response by increasing the service level.

(6) When the platform provides additional services, an upper limit can exist on the platform's service responsiveness, within which the platform need not increase the service response speed to attract customers.

7.2 Managerial implications

Our research is motivated by the practical operation of the logistics robot sharing platform. Some of our findings may be generalized to other industrial platforms, e.g., private products and skills sharing platforms, which widely exist in practice. Our research provides several managerial implications for the management of the logistics robot sharing platform.

First, the manager of the platform should focus on how to help customers reduce the cost of using logistics robots, which is also one of the measures to improve the service level of the platform.

Second, if the logistics robot firms or customers are unwilling to join the platform, the platform should provide additional services to make up for the loss caused by the low response speed. But the level of additional services must be high enough for the platform to benefit.

Third, although an increase in the service response speed does not necessarily benefit the platform, if the platform does not have a competitive edge in the response speed, the platform can increase its own value by providing additional services.

Fourth, the pricing decision of the platform cannot consider the service quality of the platform only and high service quality cannot become a factor for the platform to increase the sharing price. The setting of the sharing price should take into consideration of the use cost of the logistics robot.

Finally, at a low service response speed, the platform should consider how to improve it rather than provide additional services. When customers are more concerned about the service response speed, there is no need for the platform to provide a high level of additional services.

7.3 Future studies

Further research may consider charging a transaction fee to the users of the platform. In addition, further research may consider that the platform provides different service quality to different customers. In future research we hope to clarify how additional services affect the demand for the platform. Other operational problems concerning logistics robot sharing should be considered as well, such as how the platform size affects the sharing decision, or under what kind of customer preference could platform sharing outperform no platform sharing.

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Appendix A. All proofs

Proof of Proposition 1: Let $\frac{\partial d^*}{\partial \theta} = -\frac{m+t-2u+c_2}{6t(1+\theta)^2} > 0$, so $t < 2u - (m + c_2)$, i.e., d increases with θ; and $\frac{\partial d^*}{\partial \theta} = -\frac{m+t-2u+c_2}{6t(1+\theta)^2} < 0$, so $t > 2u - (m + c_2)$, i.e., d decreases with θ. (Q.E.D.)

Proof of Proposition 2: $\frac{\partial {p_1}^*}{\partial \theta} = -\frac{2(2t-u+c_2)}{3\theta^2} > 0$, so $t < \frac{u-c_2}{2}$, i.e., ${p_1}^*$ increases with θ; $\frac{\partial {p_1}^*}{\partial \theta} = -\frac{2(2t-u+c_2)}{3\theta^2} < 0$, so $t > \frac{u-c_2}{2}$, i.e., ${p_1}^*$ decreases with θ; $\frac{\partial {p_2}^*}{\partial \theta} = \frac{(m+5t-u)}{6} > 0$, so $t > \frac{u-m}{5}$, i.e., ${p_2}^*$ increases with θ; and $\frac{\partial {p_2}^*}{\partial \theta} = \frac{(m+5t-u)}{6} < 0$, so $t < \frac{u-m}{5}$, i.e., ${p_2}^*$ decreases with θ. $\frac{\partial {c_1}^*}{\partial \theta} = -\frac{2t-u+c_2}{2\theta^2} > 0$, so $t < \frac{u-c_2}{2}$, i.e., ${c_1}^*$ increases with θ; $\frac{\partial {c_1}^{**}}{\partial \theta} = -\frac{2(2t-u+c_2)}{3\theta^2} < 0$, so $t > \frac{u-c_2}{2}$, i.e., ${c_1}^*$ decreases with θ (Q.E.D.)

Proof of Proposition 3: Given ${\pi_p}^* - {\pi_d}^* = \frac{[\theta(u-m-2t)+c_2-t-u]}{3}$. When $\theta(u-m-2t)+c_2-t-u > 0$, i.e., $\theta > \frac{t+u+c_2}{u-m-2t}$, we have ${\pi_p}^* - {\pi_d}^* > 0$; when $\theta(u-m-2t)+c_2-t-u < 0$, i.e., $\theta < \frac{t+u+c_2}{u-m-2t}$, we have ${\pi_p}^* - {\pi_d}^* < 0$; and when $\theta(u-m-2t)+c_2-t-u = 0$, i.e., $\theta = \frac{t+u+c_2}{u-m-2t}$, we have ${\pi_p}^* - {\pi_d}^* = 0$. (Q.E.D.)

Proof of Proposition 4: Let $\frac{\partial d^{s*}}{\partial \theta} = -\frac{m+t-2u+s\alpha+c_2}{6t(1+\theta)^2} > 0$, yield $t < 2u - (m + c_2) - s\alpha$, i.e., d^{s*} increase with θ; Let $\frac{\partial d^{s*}}{\partial \theta} = -\frac{m+t-2u+s\alpha+c_2}{6t(1+\theta)^2} < 0$, yield $t > 2u - (m + c_2) - s\alpha$, i.e., d^{s*} decrease with θ. $\frac{\partial d^{s*}}{\partial s} = \frac{\alpha}{6t+6t\theta} > 0$, i.e., d^{s*} increases with s. (Q.E.D.)

Proof of Proposition 5: Let $\frac{\partial p_1^{s*}}{\partial\theta}=-\frac{2(2t-u+s\alpha+c_2)}{3\theta^2}>0$, yield $t<\frac{u-c_2-s\alpha}{2}$, i.e., p_1^{s*} increases with θ; Let $\frac{\partial p_1^{s*}}{\partial\theta}=-\frac{2(2t-u+s\alpha+c_2)}{3\theta^2}<0$, yield $t>\frac{u-c_2-s\alpha}{2}$, i.e., p_1^{s*} decreases with θ. $\frac{\partial p_1^{s*}}{\partial s}=\frac{2\alpha}{3\theta}>0$, i.e., p_1^{s*} increases with s. Let $\frac{\partial p_2^{s*}}{\partial\theta}=\frac{m+5t-u}{6}>0$, yield $t>\frac{u-m}{5}$, i.e., p_2^{s*} increases with θ; Let $\frac{\partial p_2^{s*}}{\partial\theta}=\frac{m+5t-u}{6}<0$, yield $t<\frac{u-m}{5}$, i.e., p_2^{s*} decrease with θ. $\frac{\partial p_2^{s*}}{\partial s}=-\frac{\alpha}{6}<0$, i.e., p_2^{s*} decrease with s. Let $\frac{\partial c_1^{s*}}{\partial\theta}=-\frac{2(2t-u+s\alpha+c_2)}{3\theta^2}>0$, yield $t<\frac{u-c_2-s\alpha}{2}$, i.e., c_1^{s*} increases with θ; Let $\frac{\partial c_1^{s*}}{\partial\theta}=-\frac{2(2t-u+s\alpha+c_2)}{3\theta^2}<0$, yield $t>\frac{u-c_2-s\alpha}{2}$, i.e., c_1^{s*} decreases with θ. (Q.E.D.)

Proof of Proposition 6. With (31), we have $\frac{\partial p_1^{ss*}}{\partial\theta}=-\frac{4kt\alpha^2[2\theta(t+u-m)+(c_2+3t-m)]+4kt[6kt(1+\theta)^2(2t-u+c_2)]}{(\alpha^2-6kt\theta(1+\theta))^2}$. So when $\frac{\partial p_1^{ss*}}{\partial\theta}>0$, $\alpha^2<\frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$, when $\frac{\partial p_1^{ss*}}{\partial\theta}<0$, $\alpha^2>\frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$. With (32), we have $\frac{\partial p_2^{ss*}}{\partial\theta}=\frac{t\alpha^4+6k^2t^2(m+5t-u)\theta^2(1+\theta)^2+t\alpha^2\left[-k\left(u-3u\theta^2+m\theta(2+3\theta)+t\left(-2+6\theta+9\theta^2\right)\right)+k(1+2\theta)c_2\right]}{(\alpha^2-6kt\theta(1+\theta))^2}$. So when $\frac{\partial p_2^{ss*}}{\partial\theta}>0$, $\alpha^2<\frac{(u-2t+c_2)+3\theta^2(3t-u+m)+2\theta(3t+m+c_2)}{6kt\theta^2(1+\theta)^2(u-m-5t)}$, when $\frac{\partial p_2^{ss*}}{\partial\theta}<0$, $\alpha^2>\frac{(u-2t+c_2)+3\theta^2(3t-u+m)+2\theta(3t+m+c_2)}{6kt\theta^2(1+\theta)^2(u-m-5t)}$. (Q.E.D.)

Proof of proposition 7. With (30), we have $\frac{\partial d^{ss*}}{\partial\theta}=-\frac{k\alpha^2[2\theta(t-m+u)+(2t+c_2-u)]+k[6kt\theta^2(t+m-2u+c_2)]}{(\alpha^2-6kt\theta(1+\theta))^2}$. So when $\frac{\partial d^{ss*}}{\partial\theta}>0$, $\alpha^2<\frac{6kt\theta^2(2u-t-m-c_2)}{2\theta(t+u-m)+(2t+c_2-u)}$, when $\frac{\partial d^{ss*}}{\partial\theta}<0$, $\alpha^2>\frac{6kt\theta^2(2u-t-m-c_2)}{2\theta(t+u-m)+(2t+c_2-u)}$. With (29), we have $\frac{\partial {c_1}^{ss*}}{\partial\theta}=-\frac{3kt\alpha^2[2\theta(t+u-m)+c_2-m+3t]+3kt[6kt(1+\theta)^2(2t-u+c_2]}{(\alpha^2-6kt\theta(1+\theta))^2}$. So when $\frac{\partial {c_1}^{ss*}}{\partial\theta}>0$, $\alpha^2<\frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$, when $\frac{\partial {c_1}^{ss*}}{\partial\theta}<0$, $\alpha^2>\frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$. With (28), we have

$\frac{\partial s^*}{\partial \theta} = \frac{(m-t-u)\alpha^3+\alpha\left[6kt\left(-m\theta^2+u(-1-2\theta+\theta^2)+t(2+4\theta+\theta^2)\right)+6kt(1+2\theta)c_2\right]}{(\alpha^2-6kt\theta(1+\theta))^2}$. So when $\frac{\partial s^*}{\partial \theta} > 0$, $\alpha^2 < \frac{6kt[\theta^2(t-m+u)+(2t-u+c_2)(2\theta+1)]}{m-t-u}$. When $\frac{\partial s^*}{\partial \theta} < 0$, $\alpha^2 > \frac{6kt[\theta^2(t-m+u)+(2t-u+c_2)(2\theta+1)]}{m-t-u}$.

(Q.E.D.)

Proof of Proposition 8: Under scenario 1, we have $u_3 < u_1$, $u_3 < u_2$, and $u_1 < u_2$. Solving these inequalities, we obtain $\theta < \frac{\alpha_2 s}{p_2^s - p_1}$, $\theta < \frac{\alpha_2 s}{[p_2^s - p_2 + t(2d-1)]}$, and $p_1 \leq p_2 + t(1-2d)$. From the three results, we derive that $\theta < \frac{\alpha_1 s}{p_1^s - p_1}$. Under scenario 2, we first consider $\begin{cases} u_2 < u_1 \\ u_2 < u_{1-2} \end{cases}$. Solve this system of inequalities, we derive the contradictory result that $\begin{cases} p_1 < p_2 + t(1-2d) \\ p_1 > p_2 + t(1-2d) \end{cases}$. So, scenario 2 is rejected. Similarly, scenario 3 is also rejected. (Q.E.D.)

Appendix B. Summary of sensitivity analyses

Table B1. Optimal solutions and sensitivity analyses towards θ in basic model

Optimal solutions	θ
$d^* = \frac{\theta(t+u-m)+(2t+c_2-u)}{3t(\theta+1)} \uparrow$	$\uparrow$, if and only if $t < 2u-(m+c_2)$ $\downarrow$, if and only if $t > 2u-(m+c_2)$
${p_1}^* = \frac{\theta(m+2u+2t)+2(2t+c_2-u)}{3\theta} \uparrow$	$\uparrow$, if and only if $t < (u-c_2)/2$ $\downarrow$, if and only if $t > (u-c_2)/2$
${p_2}^* = \frac{\theta(m-u+5t)+(4t+5c_2+u)}{6} \uparrow$	$\uparrow$, if and only if $t > (u-\mathrm{m})/5$ $\downarrow$, if and only if $t < (u-\mathrm{m})/5$
${c_1}^* = \frac{\theta(m+t+u)+(2t-u+c_2)}{2\theta} \uparrow$	$\uparrow$, if and only if $t < (u-c_2)/2$ $\downarrow$, if and only if $t > (u-c_2)/2$

Table B2. Optimal solutions and sensitivity analyses towards θ and s in extended models

Optimal solutions	θ	s
$d^{s*} = \frac{\theta(t-m+u)+(c_2+2t-u)+s\alpha}{6t+6t\theta} \uparrow$	$\uparrow$, if and only if $t < 2u-(m+c_2)-s\alpha$ $\downarrow$, if and only if $t > 2u-(m+c_2)-s\alpha$	$\uparrow$
$p_1^{s*} = \frac{\theta(m+2u+2t)+2(t+c_2-u)+2s\alpha}{3\theta} \uparrow$	$\uparrow$, if and only if $t < (u-c_2-s\alpha)/2$ $\downarrow$, if and only if $t < (u-c_2-s\alpha)/2$	$\uparrow$
$p_2^{s*} = \frac{\theta(m-u+5t)+(4t+5c_2+u)-s\alpha}{6} \uparrow$	$\uparrow$, if and only if $t > (u-\mathrm{m})/5$ $\downarrow$, if and only if $t < (u-\mathrm{m})/5$	$\downarrow$
${c_1}^* = \frac{\theta(m+t+u)+(2t-u+c_2)+s\alpha}{2\theta} \uparrow$	$\uparrow$, if and only if $t < (u-c_2-s\alpha)/2$ $\downarrow$, if and only if $t < (u-c_2-s\alpha)/2$	$\uparrow$

Table B3. Optimal solutions and sensitivity analyses towards θ in extended models

Optimal solutions	θ
$d^{ss*} = \frac{k\theta[(2t-u+c_2)+\theta(t+u-m)]}{6kt\theta(1+\theta)-\alpha^2}\uparrow$	$\uparrow$, if $\alpha^2 < \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$ $\downarrow$, if $\alpha^2 > \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$
$p_1^{ss*} = \frac{2kt(1+\theta)[\theta(m+2u+2t)-2u+4t]+4kt(1+\theta)c_2-m\alpha^2}{6kt\theta(1+\theta)-\alpha^2}\uparrow$	$\uparrow$, if $\alpha^2 < \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$ $\downarrow$, if $\alpha^2 > \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$
$p_2^{ss*} = \frac{t(1+\theta)[k\theta(4t+u+\theta(m+5t-u))-\alpha^2]+[\alpha^2-5kt\theta(1+\theta)]c_2}{6kt\theta(1+\theta)-\alpha^2}\uparrow$	$\uparrow$, if $\alpha^2 < \frac{(u-2t+c_2)+3\theta^2(3t-u+m)+2\theta(3t+m+c_2)}{6kt\theta^2(1+\theta)^2(u-m-5t)}$ $\downarrow$, if $\alpha^2 < \frac{(u-2t+c_2)+3\theta^2(3t-u+m)+2\theta(3t+m+c_2)}{6kt\theta^2(1+\theta)^2(u-m-5t)}$
$c_1^{ss*} = \frac{6kt^2-m\alpha^2+3k[t(c_2-u)+\theta(mt+3t^2+tc_2)+t\theta^2(m+t+u)]}{6kt\theta(1+\theta)-\alpha^2}\uparrow$	$\uparrow$, if $\alpha^2 < \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$ $\downarrow$, if $\alpha^2 > \frac{6kt(1+\theta)^2(u-2t-c_2)}{2\theta(t+u-m)+(c_2-m+3t)}$
$s^* = \frac{\alpha[(2t-u+c_2)+\theta(t+u-m)]}{6kt\theta(1+\theta)-\alpha^2}\uparrow$	$\uparrow$, if $\alpha^2 < \frac{6kt[\theta^2(t-m+u)+(2t-u+c_2)(2\theta+1)]}{m-t-u}$ $\downarrow$, if $\alpha^2 > \frac{6kt[\theta^2(t-m+u)+(2t-u+c_2)(2\theta+1)]}{m-t-u}$

Appendix C. Notation used in the paper

Table C. Notions used in the paper

Notation	Explanation
U_p	Utility of customers on the LRS platform
U_d	Utility of customers not on the LRS platform
u	Maximum utility of a customer obtained
t	Unit cost of using logistics robots
m	Operating costs of the LRS platform
c_1	Service fees that the logistics robot firms pay to the platform
c_2	Cost of logistics robot firms without the LRS platform
α	Customers' sensitive coefficients to additional services
s	Additional services level
θ	Service response speed
d	Demand of logistics robots
π_p	Profit of logistics robot firms with the LRS platform
π_d	Profit of logistics robot firms without the LRS platform
π_{LRSP}	Profit of the LRS platform
p_1	Sharing price with the LRS platform
p_2	Sharing price without the LRS platform

Note that superscript "*" represents the optimal decisions, superscript "s" represents the case that exogenous additional services are considered, superscript "ss" represents that the case that Endogenous additional services are considered.