

A Bi-Level Approach For Optimal Design of Robotic Food Delivery Services

Anke Ye ^{a,b}, Jun Li ^c, Xin Liu ^d, Michael GH Bell ^c, Xiqun (Michael) Chen ^b, Simon Hu ^{a,*}

(a) ZJU-UIUC Institute, Zhejiang University, Haining 314400, China; (b) College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China; (c) Institute of Transport and Logistics Studies (ITLS), Business School, the University of Sydney, NSW 2006, Australia; (d) Department of Procurement Management, China National Aviation Fuel Group Ltd., Beijing 100088, China; (*) Corresponding author. Email address: simonhu@intl.zju.edu.cn.

BACKGROUND

With the advent of digital economy and our fast-paced modern lifestyle, the food delivery market is growing dramatically, further boosted with the recent event of the COVID-19 pandemic. The price for Courier-based Food Delivery Services (CFDSs) on the most popular platforms varies from \$1 to \$10 depending on the distance, the order fees and whether the order takes place during busy hours. In response to the growing demand and surging labour costs, projects based on the idea to deploy autonomous vehicles/robots instead of traditional couriers are pushed forward. As a result, AV manufacturers and e-commerce giants have continuously launched live beta programs of Robotic Food Delivery Services (RFDSs). The majority of their existing delivery processes can be described as follows: (1) A number of robots, those are only able to serve one order at once, wait at a restaurant; (2) When an order occurs, a robot sends the order directly from the restaurant to the appointed location of the customer.



Figure 1: Autonomous delivery robots of Starship (left), Kiwi (middle) and UberEats (right)

Startups, such as Starship and Kiwi, have launched their RFDSs by small robots moving only on sidewalks with a price of \$1-\$4 per order, which are appealing to customers (see Figure 1). However, compared with the expected low service price for the delivery, the fixed cost for an autonomous robot is estimated at \$5,500 (for a small size) and \$300,000 (for a mini-van size) respectively. With the advancement of autonomous vehicle technology, the price of robots are expected to be reduced in the near future. The efficiency of such RFDS will be improved through faster travelling speed and larger capacity. On this basis, current research aims to explore the opportunity of a new promising alternative (RFDS system) for food delivery service in the future and formulate its potential operational models. The focus of this study lays on the pricing problem of RFDS: whether the novel service can achieve cost-effectiveness in the existing food delivery market dominated by CFDS.

PROBLEM FORMULATION AND METHODOLOGY

This work proposes a two-stage food delivery system consisting of an autonomous vehicle manufacturer (i.e. robot company), cooperative restaurants and customers (see Figure 2). The system provides a business model of lease-based robotic food delivery services as an alternative to labour delivery services under food order demand uncertainty. The system is to

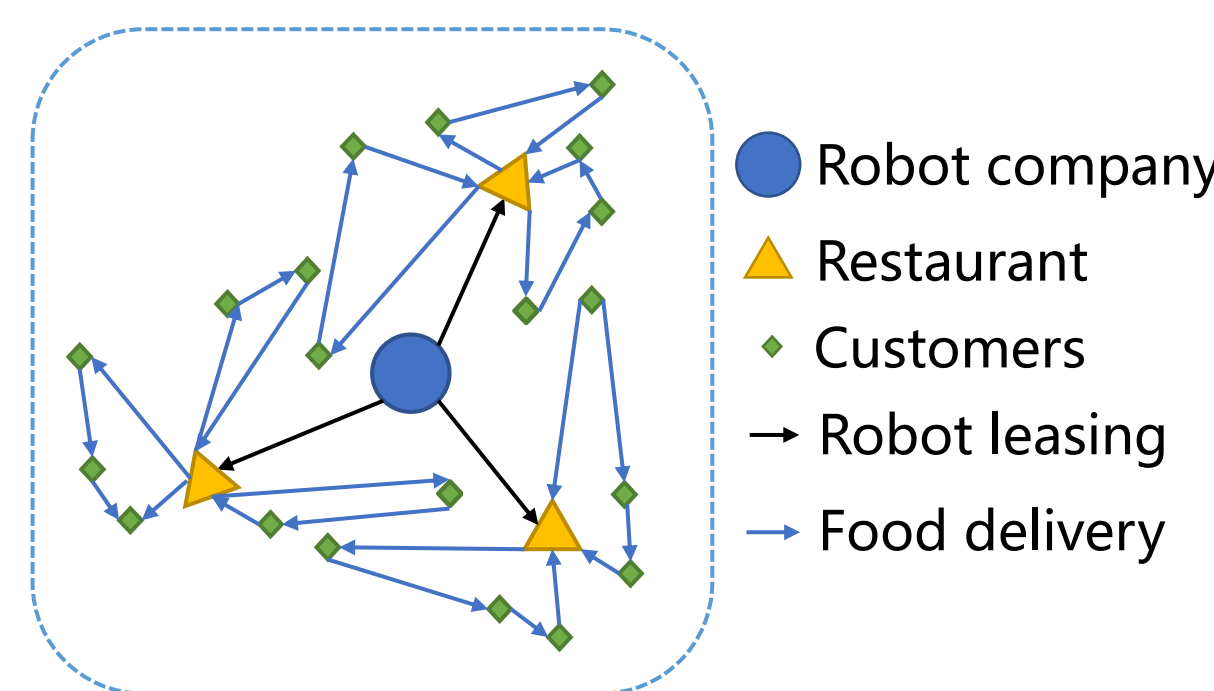


Figure 2: Service process of RFDS

investigate the optimal robot demand, inventory and unit price under the consideration of food order uncertainty to achieve a maximal profit for both the robot company and the restaurant.

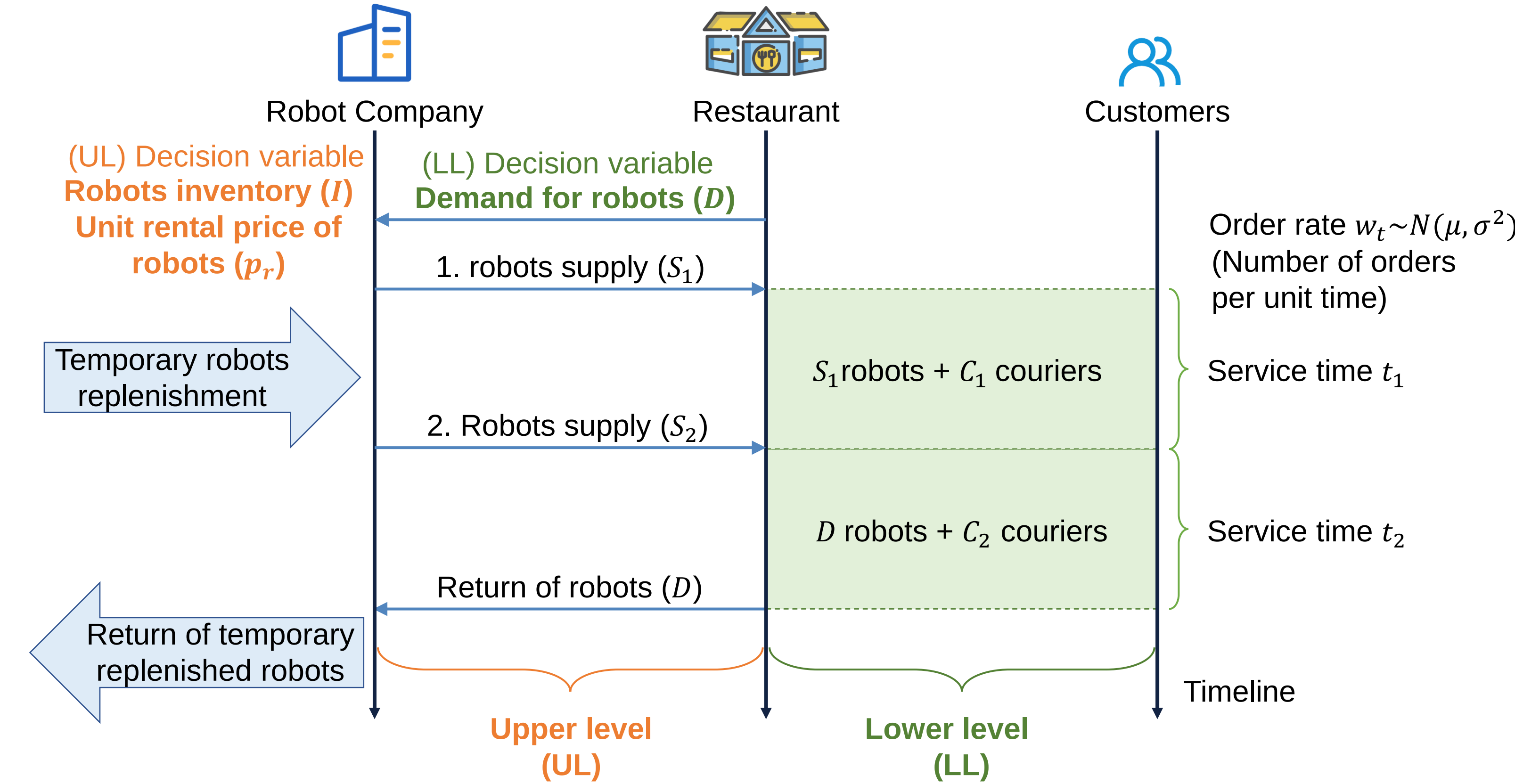


Figure 3: Lease-based RFDS model within the time horizon of one day

Bi-level programming is implemented to calculate the optimal unit price of an autonomous delivery robot and the demand for robots to serve existing food orders.(see Figure 3). The upper level (UL) describes the robot lease process between the robot company and the restaurant with the objective to maximize the profit of the robot company (revenue – costs for inventory – costs and penalty for understock):

$$\max_{I, p_r} J_U = D \cdot p_r - I \cdot p_I - (D - S_1)(p_{us} + c_{replenish})$$

with variables: I – the robot company's inventory, p_r – the unit price of a robot for one day, S_1 – the number of robots in first supply ($S_1 = \min(D, I)$); and parameters: D – the restaurant's demand for robots, p_I – inventory cost of a robot for one day, p_{us} – penalty for understock of each robot, $c_{replenish}$ – price for temporarily dispatch of each robot from other affiliates.

The objective in the lower level (LL) is to maximize the profit of the restaurant (expected revenue $E[RE]$ – expected costs for couriers $E[CC]$ – costs for robots), which depends greatly on the decision of the combination of delivery robots and couriers:

$$\max_D J_L = E[RE] - E[CC] - D \cdot p_r$$

with a variable: D – the restaurant's demand for robots; a parameter: p_r – the unit price of a robot for one day.

Despite the complexity of the objective function after normalization and reformulation,

the problem is efficiently solved by the enumeration method due to the low dimension and limited range of the solution domain.

CASE STUDY

The influence of different order rates and robot service efficiency is investigated through a case study (see Figure 4 and Figure 5). The results indicate that: (1) The maximal profit of the robot company and the restaurant is increased with growing food delivery orders; (2) The robot can be priced higher with an annual rental (optimal unit rental price x 365) of \$101,470 – \$149,650, as the order rate increases from 40 to 80 orders per hour (robot service efficiency = 6 orders/h); (3) The optimal unit price of robots can be raised dramatically as their service efficiency improves; And (4) the improving service efficiency of robots contributes to higher profit for the robot company and lower delivery cost per order for the restaurant.

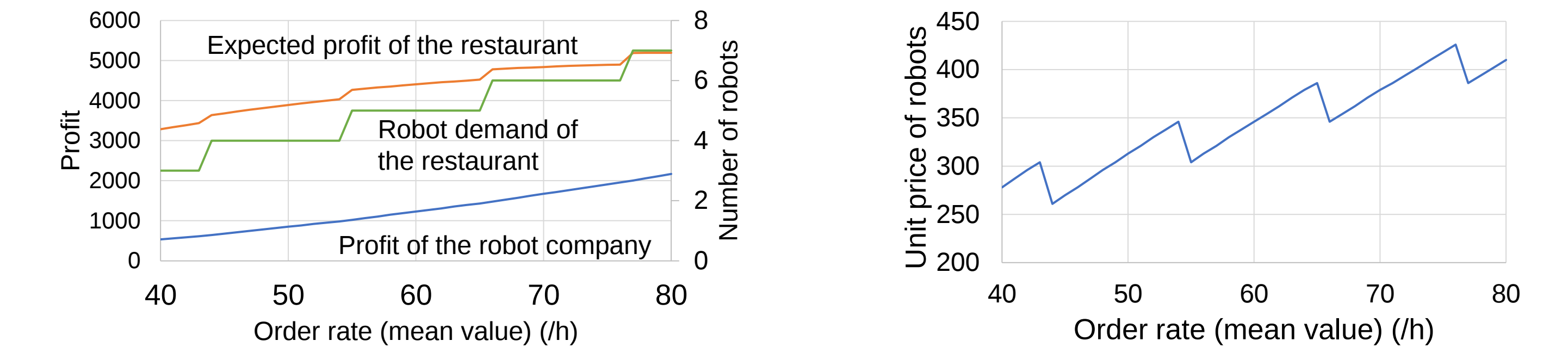


Figure 4: Optimal solutions influenced by different order rate

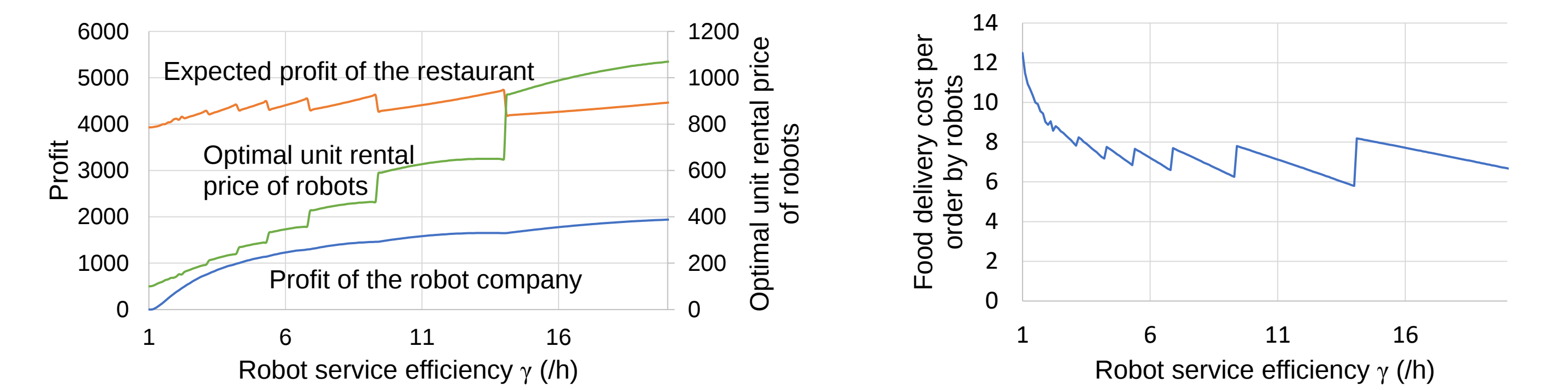


Figure 5: Optimal solutions influenced by different robot service efficiency

CONCLUSIONS AND FUTURE RESEARCH

This study develops a leasing business model of robotic food delivery services as an alternative to traditional delivery services. The problem is formulated as a bi-level programming model to maximize the profit of the robot company and the restaurant while considering demand uncertainties. The analysis of economic factors of RFDS in comparison with traditional CFDS is conducted based on the model. The surge pricing strategy of CFDS is beneficial for a lifting price of RFDS as the demand for food delivery service is growing. By improving the robot service efficiency, both the robot company and the restaurants are able to achieve higher profits, while the delivery cost per order can be reduced. Future work will seek to take into consideration of (1) the sensitivity of food order demand to the price of delivery services and (2) heterogeneous robot service efficiency (related to restaurant location and order time).