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An IoT-based E-business model of intelligent vegetable greenhouses and its key operations management issues

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Abstract

The widespread popularization of Internet has brought about various Internet-based business models as well as well-known Internet giants such as Facebook, Google, Amazon, and Alibaba. Similarly, the application of internet of things (IoT) is fermenting IoT-based business models in various fields. In our work, we present an IoT-based e-business model of intelligent vegetable greenhouses with details on the basic process and key nodes of the e-business model. Information, capital and logistics flows are recognized in the industry chain consisting of ingredient suppliers, IoT-equipped greenhouses, IoT-based e-business platforms, payment and delivery service providers, and end consumers. The value chain is also analyzed according to Michael Porter's value chain model, which is helpful for greenhouses to focus on main activities in the business model. Moreover, we recognize key operation issues including big-data-driven pricing, planting structure and time optimization, water and fertilizer integrated control, plant light supplement, and order-driven picking and packing. The characteristics brought about by IoT techniques to these operation issues are analyzed, and corresponding mathematical models are formulated, which may attract more efforts in the future.

Keywords Intelligent vegetable greenhouses · Internet of things · E-business model · IoT-based e-business platforms · Industry and value chains · Operations management

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1 Introduction

The connectivity in internet of things (IoT) is far more expansive than the current Internet. In the era of IoT, physical things and digital components are not only connected but also can communicate with each other, without the intervention of the people. This capacity of IoT is reshaping the business process in various industries such as transportation, manufacturing, healthcare, and agriculture [1, 5, 14, 36]. Innovative IoT-related products and services surely become new profit sources with competitive advantages [9–11, 24]. In the agricultural sector, IoT has attracted a tremendous surge of attentions from both the literature and practical companies. In Microsoft's FarmBeats project, increasing efforts have paid to improve farm productivity and reduce costs using IoT techniques [20]. Intel put forward a slogan: "Feed the world—with IoT" and witnessed the efficacy of IoT systems in increasing food production [12]. In September, 2018, Alibaba and Kingland Tech signed an agreement trying to reshape the agricultural sector using IoT and big data techniques [35].

Greenhouses are one of early practices to carry out precision agriculture, and are recognized exactly important to meet the vegetable demand of human kinds especially in extreme regions. As reviewed in Sect. 2, IoT devices including sensors, actuators and drones have been well reported to improve the management efficiency and precision of greenhouses [4, 15, 19, 32]. However, few studies focus on new changes brought about by IoT systems to the business of greenhouses. This research gap is also one major concern of greenhouse farmers when they decide whether to implement IoT devices in their greenhouses, because most of farmers are non-tech-savvy and have limited interest on the implementation of IoT systems [20, 28]. Meanwhile, operations management, whose performance has direct impact on the costs and revenues of any organization, can be improved greatly in the environment of IoT. However, existing agriculture IoT studies do not formulate a systematic IoT-based e-business model for greenhouse farmers, and corresponding operations management is not analyzed in details. Motivated by these observations, we propose an IoT-based e-business model of intelligent vegetable greenhouses and analyze corresponding operations management issues.

To sum up, we have the following incremental contributions to the literature:

1. A system framework of IoT-based intelligent vegetable greenhouses is formulated, with specific analysis on the different roles of greenhouse farmers, agricultural specialists, system administrators and consumers in the IoT system from those in traditional business models.
2. An IoT-based e-business model of vegetable greenhouses is proposed and key nodes in the business model are recognized. Its industry chain is specified from information flow, capital flow and logistics flow, and its value chain consisting of primary and support activities is discussed according to Michael Porter's framework.
3. Operations management issues in the IoT-based e-business model are recognized and corresponding mathematical models are formulated to minimize operation costs or maximize vegetable revenues.

The rest of the work is organized as below. In Sect. 2, we have a brief review on advances on IoT-based greenhouses and IoT-based business models. Section 3 details our IoT-based e-business model as well as corresponding industry and value chain. In Sect. 4, we analyze five key operations management issues in the IoT-based e-business model. We conclude the work in Sect. 5.

2 Literature review

2.1 Advances on IoT-based greenhouses

IoT-related sensors and actuators are well recognized helpful to improve the management efficiency of greenhouses and the quality of greenhouse products. A lot of related advances have been reported in the literature. Kampianakis et al. [15] agreed that wireless sensor network (WSN) is helpful to implement precision agriculture, developed an analog scatter-radio WSN, and observed the advantages of their WSN design in a tomato greenhouse. Srbinovska et al. [33] presented a WSN architecture for vegetable greenhouses, analyzed the characteristics of greenhouse environment, and designed a low-cost greenhouse monitoring system. Sharma et al. [31] made a comparison on the potential of two capacitance sensors and proposed crop coefficients ($K - c$) for the greenhouse chile pepper production. Liao et al. [16] presented an IoT-based monitoring system of orchid greenhouse environment and the growth status of Phalaenopsis. Aiello et al. [1] presented a decision support system with multisensor decision fusion methodology which can be applied in greenhouse production for reducing the use of pesticides and fertilizers. More reports on the application of IoT techniques in greenhouses can be found from Azfar et al. [3] and Shamshiri et al. [30].

Besides sensors and actuators, IoT-based robots and drones are also applied in greenhouses. Nissimov et al. [21] thought obstacle detection is very important for agricultural robots and used the Kinect 3D sensor to design an obstacle detection method for robotic spray vehicles in greenhouses.

Barth et al. [4] reported an eye-in-hand sensing and motion control system for agricultural robotics in dense vegetation, and tested the effectiveness of their system using simulated sweet-pepper harvesting. Simon et al. [32] argued that drones are gradually used to collect data, and proposed a dynamic model for a hexa-rotor drone to achieve the navigation of drones in greenhouse environment.

As we can see, various IoT devices including sensors, actuators, drones and robots have been applied into environment monitoring, precision irrigation and fertilization, and pest control in greenhouses. These applications are helpful for greenhouses to improve management efficiency and precision, but surely bring about high investment on IoT devices. Corresponding business models are needed to motivate greenhouse farmers to implement the IoT system in their greenhouses. Meanwhile, key operations in IoT-equipped greenhouses have direct impact on the costs and revenues of greenhouses. Unluckily, few studies focus on the business models of IoT-equipped greenhouses as well as the key operations management issues.

2.2 Advances on IoT-based business models

One of the main differences of IoT from Internet is that things besides people are connected and can communicate with each other [10, 34]. The automatic connection and communication among things will reshape traditional business processes, greatly. A few studies have recognized the revolution and possible business trends in the era of IoT, as below.

Radio frequency identification devices (RFID), as a kind of early IoT devices, get initial attentions. Asif and Mandviwalla [2] described how RFID systems consisting of tags, readers and antennas work in the supply chain and found that initial adopters need considerable efforts to apply RFID systems into their existing business processes. Wamba et al. [38] analyzed the impacts of RFID and EPC (Electronic Product Code) on mobile B2B eCommerce, and used a business process approach to find that these two techniques can improve and trigger automatically business processes to form a higher information sharing mechanism.

Recently, more and more studies are reported on IoT driven business models. Perera et al. [25] were inspired by infrastructure, platforms and software as services to present sensing as a service model, and analyzed the challenges and issues when implementing the new service model in practical business. Qiu et al. [27] applied IoT systems into the sharing of physical assets and services in supply hub in industrial park, introduced a concept of physical asset service system as a new business model, and discussed some future research directions including IoT infrastructure and business models. Dijkman et al. [9] presented a business model framework for IoT applications consisting of building blocks and types of options for each building block. Palattella et al. [22] agreed that IoT will bring about new services to reshape our current life and work ways, and observed massive business shifts caused by an integration of IoT and 5G. Christidis et al. [8] analyzed how the combination of blockchain and IoT facilitates services and resources sharing, and concluded that the combination can bring about new business models and novel applications. Weinberger et al. [40] proposed a concept of high-resolution management and used the St. Gallen Business Model Navigator to analyze how IoT affects industrial processes. Ghanbari et al. [10] discussed the relevance of vertical cooperation in the era of IoT and observed the need to develop new value networks and create new business models. Zhang and Wen [42] stated that IoT becomes a new platform for e-business and proposed an IoT e-business model with a new transaction mechanism of property and paid data using blockchain technology. In addition, some studies analyzed the impact of IoT on the business process of specific industries such as manufacturing [5, 36], assembly [39], and food [23].

Although it is well recognized that IoT can create new business models by the capacity of connecting physical things with digital components, more efforts are in urgent need to popularize these new IoT-based business models. One is to build the IoT infrastructure especially in agriculture areas. Governments should undertake the money-consuming infrastructure construction such as high-speed communication networks. Another effort is to develop IoT-based business platforms which can provide transparent connections between customers and agri-products. Existing Internet giants have great potential by updating their Internet services to IoT services. The third one is to decrease the costs of IoT devices, which could prompt more non-tech-savvy farmers to implement IoT systems. As reviewed in Sect. 2.1, IoT devices have been adopted in greenhouses for improving growth efficiency and quality of agri-products. However, it is still an open issue to innovate new business models for intelligent greenhouses in the era of IoT. Motivated by this research gap, we present an IoT-based e-business model of intelligent vegetable greenhouses.

2.3 Advances on IoT-based operations

Operations management is one of the major functions in any organization, aiming at providing optimal goods or services with limited input constraints, so the level of operations management has great impact on the costs and revenues of one organization [13, 17, 41]. IoT as well as any innovative technique may reshape the existing operations management.

In recent years, operations research using IoT techniques has been reported in the literature. Louis and Dunston [17] applied IoT systems to redesign the construction operations and demonstrated the performance of the IoT-enabled control on the construction worksite. Chai et al. [6] proposed a Plan-Do-Study-Act method of deploying IoT buttons in hospital systems to deliver real-time notifications in public-facing tasks. Tong et al. [37] applied flight sensor data to develop an aircraft landing speed prediction model and proved the advantage of their model using experiments. Chemodanov et al. [7] proposed an IoT-based decision supporting framework and an Artificial Intelligent (AI)-augmented geographic routing approach to deal with the high mobility challenge in disaster responses. Xu et al. [41] integrated IoT and cloud techniques to build a fleet management platform for facilitating the operations of prefabrication transportation.

The above studies have shown the great potential of applying IoT techniques to improve the level of operations management in various fields such as construction [17, 41], healthcare [6], aviation [37], and disaster management [7]. As partly reviewed in the Introduction and Sect. 2.1, IoT will bring about obvious improvements on agriculture production by achieving precision agriculture. However, existing agriculture IoT studies do not formulate a systematic IoT-based e-business model for greenhouse farmers, and corresponding operations management is not analyzed in details. Our work will fill the gap to help greenhouse farmers be incorporated into the IoT-based business revolution.

3 An IoT-based E-business model of intelligent vegetable greenhouses

3.1 IoT-based intelligent vegetable greenhouses

As reviewed in Sect. 2, the overwhelming majority of studies on IoT-based greenhouses are related to the technique issues in the implementation, such as environment control [16], obstacle detection [21], and harvesting [4]. Based on the existing researches, we formulate a system framework of IoT-based intelligent vegetable greenhouses, as Fig. 1 shows. Considering the scale effect and required investments on IoT devices, in this work, we focus on framers with certain scale greenhouses. Even in smallholder countries such as China and Japan, most greenhouse farmers tend to expand their greenhouses to a certain scale.

3.1.1 Related bodies of IoT-based intelligent vegetable greenhouses

Four kinds of related bodies are involved in the IoT-based greenhouses with different roles in the system from those in traditional business models, as Table 1 shows.

1. *Greenhouse farmers* IoT devices are well recognized to have greatly enhanced farmers' efficiency in greenhouses. In traditional conditions, greenhouse farmers have to regularly step in greenhouses for checking the inside environment and manually operate corresponding adjustment devices. These works are so time consuming that farmers have to employ enough workers which result in high costs. With the support of IoT monitoring and control devices, farmers just sit in the monitoring room and occasionally go to check specific greenhouses with warning signals. A majority of labor costs are reduced to manage the IoT-equipped greenhouses.
2. *Agricultural specialists* The productivity of vegetable greenhouses is highly dependent on the knowledge and experiences of agricultural specialists. Considering the limitation of operation costs, most vegetable greenhouses even for large-scale farms will not employ specialists in various fields. The common practice adopted by traditional greenhouses is that specialists are invited to greenhouses when serious diseases and insect pests happen. Thus, disaster losses are often inevitable since the treatment measures suggested by specialists usually lag. However, these disease and pest disasters can be effectively reduced for IoT-equipped greenhouses. Vegetable specialists can at any time check the growth environment and historical records collected by IoT sensors, recognize the possible diseases and insect pests in the future, and inform farmers to take prevention measures which may avoid the losses.
3. *System administrators* The roles of system administrators mainly have the following three aspects. Firstly, they need to maintain the data processing servers where historical greenhouse data and preset warning rules are stored. A few large-scale vegetable greenhouses may have their owned servers and employ full-time system administrators, but most greenhouses tend to hire servers in Internet companies. The second role of system administrators is to help farmers control devices in greenhouses. Warning and control rules are preset in the servers and will be automatically activated when the greenhouse environment meets these rules. Moreover, consumers who would like to buy the vegetables produced by these IoT greenhouses may need the help of system administrators. Consumers

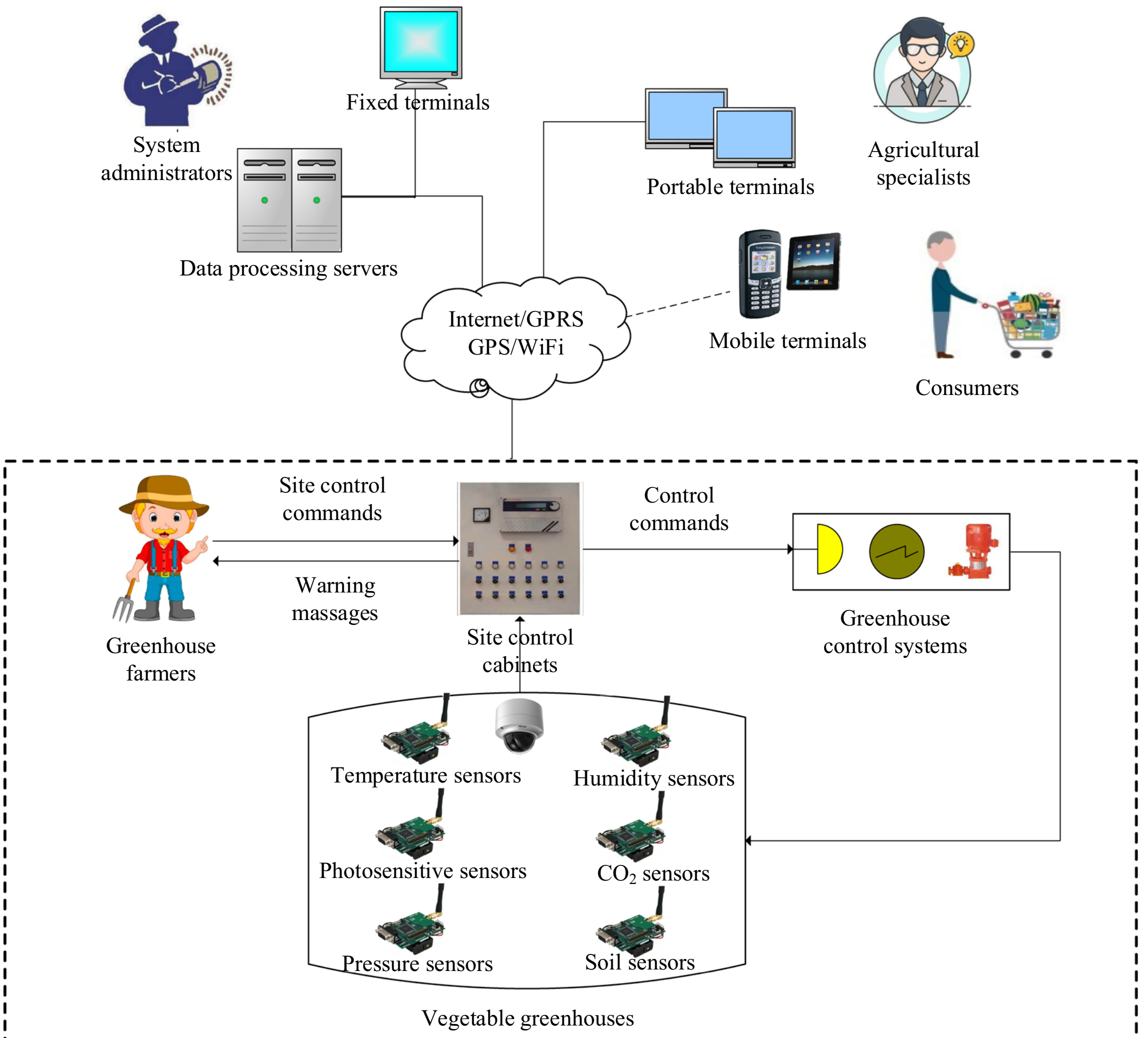

Fig. 1 A system framework of IoT-based intelligent vegetable greenhouses

Table 1 The differences of related greenhouse bodies between IoT business model and traditional business model

Related greenhouse bodies	Traditional business model	IoT business model
Greenhouse farmers	Difficult to monitor in real time	Easy to monitor in real time
	Regularly step in greenhouses	Occasionally go to greenhouses
	Low efficiency and high labor investment	High efficiency and low labor investment
Agricultural specialists	Go to greenhouses for checking diseases and insect pests	Remotely monitor diseases and insect pests
	Difficult to predict diseases and insect pests	Possible to predict diseases and insect pests
	Treatment-oriented	Prevention-oriented
System administrators	Often full-time and with limited tasks	Often part-time and with extensive tasks
	Maintain local area networks	Maintain extensive networks
	Few interactions with specialists and consumers	Frequent interactions with specialists and consumers
Consumers	Difficult to know the growth process of agri-products	Easy to know the growth process of agri-products
	Difficult to avoid food safety problems	Easy to avoid food safety problems
	Difficult to recall inferior agri-products	Easy to recall inferior agri-products

need to be authorized by administrators to check the growth status of vegetables in the IoT-equipped greenhouses. If the access is not available, administrators are helpful to fix consumers' authority.

4. *Consumers* IoT systems can greatly change consumers' buying processes and behaviors. Consumers are directly connected with the greenhouses by IoT systems, so consumers can know the growth process of these vegetables. This connection will greatly reduce food safety problems which often happen in traditional business models. Customers also can be informed timely in case that there are some food safety problems. Innovative vegetable sale models may be conducted to consumers, such as pre-sale model and subscription model.

3.1.2 Functional subsystems of IoT-based intelligent vegetable greenhouses

As Fig. 1 shows, the framework of IoT-based intelligent vegetable greenhouses consists of multiple functional subsystems, that is, greenhouse wireless sensor subsystem, greenhouse warning and control subsystem, data processing subsystem, and user access subsystem. These subsystems have different functions provided by IoT devices and are connected by network communication subsystem. These incremental functions are detailed as follows.

1. Greenhouse wireless sensor subsystem

Wireless sensor subsystem is at the lowest level in the framework. The basic function is to sense the growth environment and status. The environment sensors are common to collect the temperature, humidity, illumination intensity, CO_2 intensity, pressure and so on inside and outside greenhouses. Recently, new types of sensors have been reported to sense the growth status of vegetables, such as growth rate sensors, stem diameter sensors, and odor sensors [1]. Using these sensors, wireless sensor subsystem can send the growth environment and status of vegetables to site control cabinets and data processing servers.

2. Greenhouse warning and control subsystem

There are two kinds of greenhouse control modes, that is, site control and remote control. Site control is conducted through site control cabinets by farmers in vegetable greenhouses. When farmers recognize abnormal warnings, they often go to specific greenhouses for checking the situations and conducting necessary operations through the inside control cabinets. Remote control is automatic usually for regularized operations such as irrigation and ventilation. When the environment meets preset control rules in processing servers, commands will be automatically sent to control devices.

3. Data processing subsystem

When processing servers receive data from the wireless sensor subsystem, statistical and analytical functions preset in the servers will be conducted. Analysis results are reported back to greenhouse farmers, agricultural specialists, and customers who play their roles according to these analysis results. If regular control rules are met, control devices will be activated based on the feedback information. That is to say, the accuracy and precision of the analysis results have great impact on other related parts. As we can see, data processing subsystem is the key of the IoT-based vegetable greenhouses.

4. User access subsystem

As mentioned above, greenhouse farmers, system administrators, agricultural specialists and customers are users involved in the framework. With the support of fixed, portable or mobile terminals, greenhouse farmers can monitor the visual growth environment and make corresponding control operations to specific abnormal situations. Agricultural specialists can check the historical growth records and timely provide farmers prevention measures to minimize the diseases and insect pests. Terminal consumers can access to the whole growth process, which can effectively avoid food safety concerns.

5. Network communication subsystem

All above users and subsystems are connected through network communication subsystems. Various networks are involved in the subsystem, such as Internet, mobile communication network (MCN), global positioning system (GPS), and wireless local area network (WLAN). For each kind of network, corresponding protocols are applied, such as domain name system (DNS) protocol in Internet, general packet radio service (GPRS) in MCN, and WiFi in WLAN.

3.2 An IoT-based e-business model of intelligent vegetable greenhouses

IoT techniques can not only reshape planting and management modes of vegetable greenhouses but also bring about innovative business models. In this work, we present an IoT-based e-business model of intelligent vegetable greenhouses. Figure 2 shows the basic process of our e-business model. As mentioned above, we present the business model for farmers with certain scale greenhouses and these greenhouses could be located around one or multiple target cities. To avoid transportation costs and loss, cross-regional supply and transportation is not permitted in the business model, that is, greenhouses around a

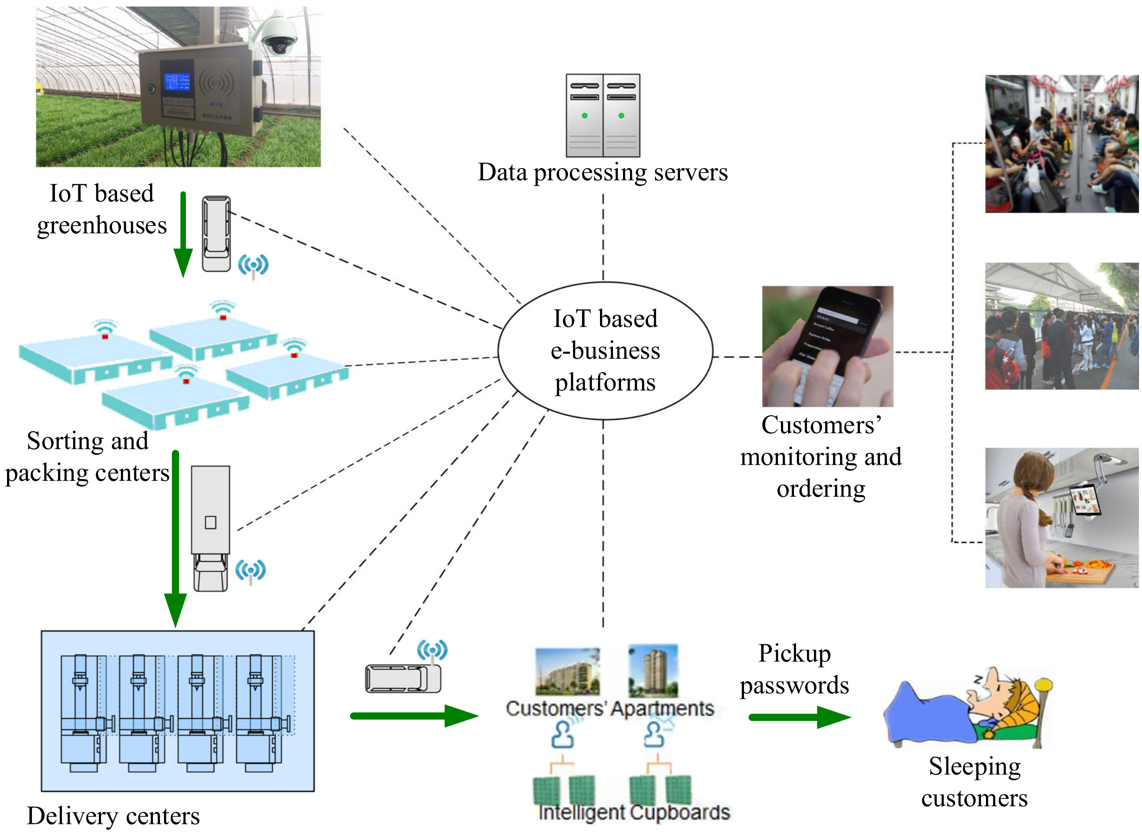

Fig. 2 An IoT-based e-business process of intelligent vegetable greenhouses

specific city only meet the demands in the city. However, the operations among cross-regional greenhouses are subject to total resource constraints. The operation objective of the business model is to maximize the profits of greenhouses, that is, to decrease costs and increase revenues as soon as possible.

In our business model, one operation rule is to make fresh vegetables available to customers in the next morning if customers make their orders before 18:00 pm. During 18:00 pm and 24:00 pm, picking and packing operations are made, so the delivery is conducted generally after 24:00 pm when customers are often sleepy. This delivery mode can avoid the traffic problem in cities during the daytime.

The details of key nodes in the business model are as below.

1. IoT-based e-business platforms

In recent two decades, Internet-based companies have emerged like bamboo shoots in spring, creating well-known Internet giants such as Facebook, Google, Amazon, and Alibaba. The success of these giants mainly depends on millions of people connected through Internet. In the coming era of IoT, it is the trend to form innovative business models. In our framework, IoT-based platforms are the foundation which connects the whole e-business process, as Fig. 2 shows. Due to financial constraints, greenhouse companies are not necessary to build their own IoT-based e-business platforms. Obviously, current Internet giants have great potential to develop into IoT giants by developing their IoT-related business.

2. Customers' monitoring and ordering

By IoT-based platforms, customers are easy to monitor the growth status of greenhouse vegetables and order their favorite vegetables. After the ordering, customers can also see the picking, packing, and delivery links through their mobile phones and portable terminals, at any time. This process assures customers of the quality of vegetables, and cuts down their purchase costs by reducing channel intermediaries such as wholesalers and retailers. Moreover, trustful connections between greenhouse farmers and customers can be built, which bring about higher incomes to framers and provide motives for greenhouse farmers to implement the IoT-based e-business model.

3. IoT-based greenhouses

In our IoT-based e-business model, greenhouses are built around target cities, that is, greenhouses do not accept orders outside their targeted cities. Thus, a fixed picking timeline, e.g., 18:00 pm, is suggested to be set. Before the picking timeline, customers in targeted cities can place their orders at any time. After the picking timeline, farmers collect customers' orders from IoT-based e-business platforms, and begin to pick kinds of vegetables. It is a difficulty to make picking plans. Greenhouse farmers have to consider constraints such as customer demands, labor resources and picking makespan to minimize picking costs. In Sect. 4, we will detail the operation.

4. Sorting and packing centers

Greenhouse farmers pick vegetables in batch and then move them to sorting and packing centers which are often selected in or close to greenhouses. At these centers, preprocessing procedures including cleaning, cutting and precooling are conducted on vegetables. More importantly, vegetables are sorted and packed according to customers' orders. All these operations at sorting and packing centers are conducted under cameras and necessary sensors. Finally, each package will be labeled with a two-dimensional (QR) code. Each QR code records identification numbers of greenhouse, growth process, picker, processer, driver, cupboard, and consumer. Through these identification numbers, the full information from farms to dining tables can be tracked.

5. Delivery centers

The packed and coded packages of vegetables are moved to delivery centers where delivery plans are made. Theoretically speaking, it is a classical vehicle routing problem to make delivery plans. Lots of studies have contributed to vehicle routing problems (VRPs), but there are differences between our delivery problem and classical VRPs. One is that vegetables are delivered to cupboards not consumers' hands. This is because the distribution in our business model is designed at night when most consumers are sleeping. Another difference is that vegetable conditions in the whole delivery process are monitored and recorded by IoT systems.

6. Intelligent cupboards

As mentioned above, vegetables will be delivered to intelligent cupboards located around end consumers. These vegetables can be with cooling functions if necessary. Once drivers put vegetables into specific cupboards, QR codes on packages will be recognized. Then, related sensors are activated according to the information in the QR codes. Pickup passwords are automatically generated and sent to consumers' phones. On the next morning, consumers or their families can go to these intelligent cupboards and pick up their vegetables. After pickups, cupboards will feedback receipt messages and corresponding video clips to IoT-based e-business platforms.

3.3 Industry chain of the IoT-based e-business model

In one business model, information, capital and logistics flows should be clearly formulated. Figure 3 specifies these flows in our IoT-based e-business model, including ingredient purchasing link, marketing link, payment link and delivery link among ingredient suppliers, IoT-equipped greenhouses, IoT-based e-business platforms, payment and delivery service providers, and end consumers.

1. Information flow

As Fig. 3 shows, information flows among almost all the participants in the business model. Greenhouse farmers make ingredient orders to suppliers according to planting plans, and post-harvesting advertisements to IoT-based e-business platforms. Consumers obtain growth data from platforms and place orders. The information flow in the IoT-based business model is with two key differences from traditional models. One is that any participant in the industry chain can access the growth status in the IoT-equipped greenhouses. The other one is that no data can be changed by any participant, because the information at any link is dealt with blockchain technologies. These differences are obviously helpful to solve the food safety problems in traditional vegetable business models.

2. Capital flow

Similar with existing e-business models, the payment link between greenhouse farmers and consumers in our model is conducted by third-party payment service providers. This payment service provides trust and protection to consumers, because payment service providers really pay consumers' money to greenhouse farmers only after consumers receive vegetables and check their quality. If there are some quality and safety problems, consumers are easy to get back their money. Of course, payment service providers also help greenhouse farmers timely and surely receive money from online consumers. The payment between greenhouse farmers and ingredient suppliers is similar if the purchasing link is conducted by IoT-based e-business platforms.

3. Logistics flow

As mentioned above, the delivery link in our business model could be conducted by either delivery service providers or greenhouse farmers themselves. If greenhouse farmers have enough operation capitals, they can purchase delivery vehicles and employ drivers. This is possible for medium-scale greenhouses, because greenhouses in our business model are built relatively close to consumers. Small-scale farmers can outsource the delivery service to third-party delivery service providers, but they need to

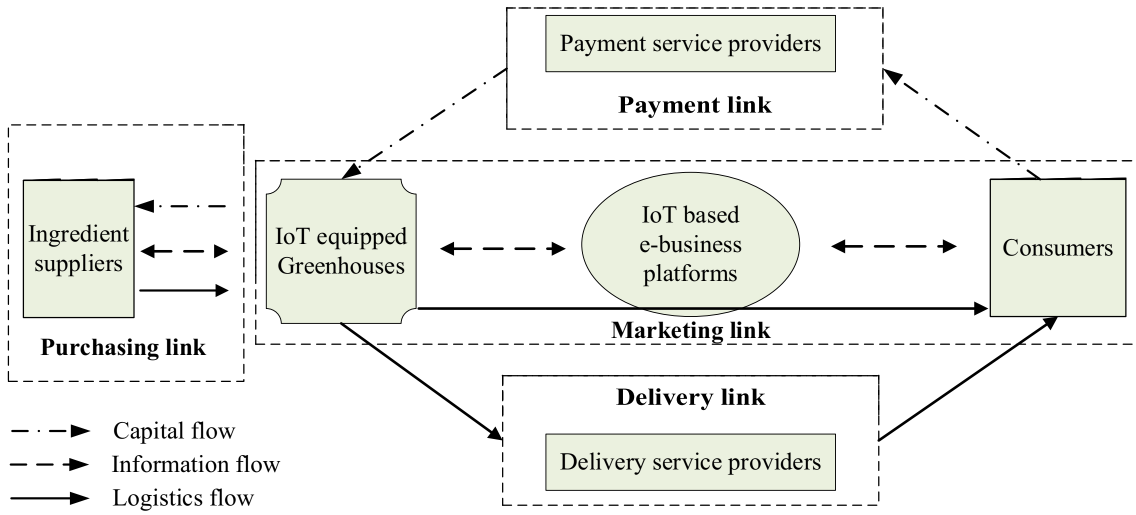

Fig. 3 The industry chain of the IoT-based e-business model

have strict requirements on the delivery services to reduce the quality loss in the delivery.

3.4 Value chain of the IoT-based e-business model

Maximal value increment is the ultimate goal of any business, but not any activity in the business can create value. Porter [26] divided business activities into primary activities and support activities [26] and formulated the famous Michael Porter's value chain model. In order to recognize the value chain of the IoT-based e-business model, we specify the key activities in the model according to Michael Porter's framework.

1. Primary activities

We recognize typical primary activities in our business model, as Table 2 details. Part of these primary activities are closely related to costs, for example, the transportation of materials, farmers, vegetable seed and seedlings, and fertilizers required at greenhouses, key greenhouse operations consisting of planting structure and time optimization, water and fertilizer integrated control, disease and pest control, as well as delivery activities to consumers. Most of the primary marketing, sales and service activities aim at maximizing revenues by making suitable prices and getting more consumers.

2. Support activities

Support activities are important for greenhouses to keep the above primary activities carry out, normally. Table 3 shows part of support activities in our IoT-based e-business model. Greenhouse farmers should pay enough attentions on these activities, part of which such as financing and quality assurance have great impact on the business performance. The activities in human resources can help greenhouses obtain enough labors and expertise, and activities in technology development are beneficial to the sustainable improvement of greenhouse performance. Procurement activities can ensure the quality of ingredient supply and build good relationships with cooperative partners.

4 Key operation issues in the IoT-based e-business model

As mentioned above, the operations management is helpful for greenhouse farmers to decrease costs and increase revenues. According to the IoT-based e-business process of intelligent vegetable greenhouses in Fig. 2, we select five operation issues, that is, big-data-driven pricing, planting structure and time optimization, water and fertilizer integrated control, plant light supplement, and order-driven picking and packing, mainly due to two reasons. One is that these operations have direct impact on the costs and revenues of greenhouses, and the other is that these operations could be greatly redesigned using IoT techniques.

4.1 Big-data-driven pricing

In any business, pricing strategies are important to maximize profits [29]. As well indicated in microeconomics, prices are determined by supply and demand in markets. In vegetable markets, the demand in a specific region, which mainly depends on population size and dietary structure in the region, is relatively easy to predict. The difficulty of vegetable pricing results from the supply, due to the

Table 2 Primary activities in the IoT-based e-business model

Primary activities	Typical corresponding activities in our business model
Inbound logistics	Transport greenhouse construction and maintenance materials to greenhouses
	Transport farmers to greenhouses
	Transport vegetable seed and seedlings to greenhouses
	Transport fertilizers to greenhouses
Operations	Planting structure and time optimization
	Water and fertilizer integrated control
	Plant light supplement
	Disease and pest control
	Order-driven picking and packing
Outbound logistics	Intelligent cupboards location
	Cupboards layout optimization
	Deliver vegetable packages to intelligent cupboards
	Transport vegetables to third-party delivery service providers
Marketing and sales	Big-data-driven pricing
	Placing vegetable information on IoT-based e-business platforms
	Serving advertisements to end consumers
	Responding to inquiries from end consumers
Service	Tracking vegetable packages for consumers
	Dealing with damaged vegetable packages
	Giving storing and cooking suggestions to consumers
	Reminding consumers to place new orders

Table 3 Support activities in the IoT-based e-business model

Support activities	Typical corresponding activities in our business model
Infrastructure	Greenhouse financing and accounting
	Greenhouse construction and maintenance
	Greenhouse daily management and control
	Vegetable quality assurance
Human resources	Recruiting system administrators and technicians
	Hiring and training greenhouse farmers
	Consulting to vegetable specialists
	Personnel performance evaluation
Technology development	Implementing advanced greenhouse facilities
	Adopting conventional and IoT-related devices
	Developing and updating greenhouse software
	Mining knowledge from greenhouse data
Procurement	Selecting ingredient suppliers
	Contracting with IoT-based e-business platforms
	Contracting with third-party payment service providers
	Selecting third-party delivery providers

following three restrictions in traditional conditions. First, it is difficult to predict the total yield and harvesting time of a specific kind of vegetable from scattered greenhouses. Second, the supply inflow across different regions is also difficult to monitor. Third, unexpected disasters such as diseases and insect pests may happen occasionally. IoT-equipped vegetable markets may greatly mitigate the difficulty. Big data in the IoT systems bring about challenges and opportunities [18]. Figure 4 presents a big-data-driven pricing of IoT-equipped vegetable markets.

Since we can get the growing status data of vegetables in IoT-equipped greenhouses, it is easy to predict the total supply at a period in one specific region and to determine the equilibrium price in the region, using the following basic model:

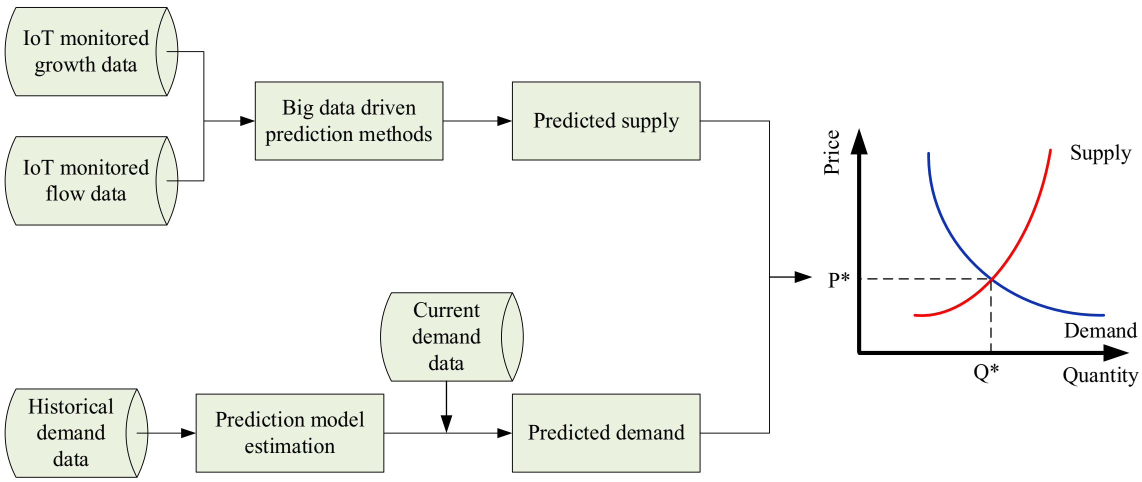

Fig. 4 A big-data-driven pricing of IoT-equipped vegetable markets

$$p^*_{ijt} = f(D_{ijt}, S_{ijt}) \quad (1)$$

$$D_{ijt} = g(p_{ijt}, p_{iat}, p_{ibt}, pop_{it}, sc_{it}, holi_{ti}, seas, \ldots,) \quad (2)$$

$$S_{ijt} = h(p_{ijt}, p_{iat}, p_{ibt}, yield_{ijt}, inflow_{ijt}, inflow_{iat}, inflow_{ibt}, seas, \ldots,) \quad (3)$$

where D_{ijt} and S_{ijt} denote the predicted demand and supply of the jth kind of vegetable at period t in region i, respectively. p_{ijt} is a variable representing the price of the jth kind of vegetable at period t in region i, p_{iat} and p_{ibt} denote the corresponding prices of two main substitute vegetables for the jth kind of vegetable, pop_{it} and sc_{it} denote the population size and consumption structure at period t in region i, respectively, $holi_{ti}$ denotes the number of holidays during period t in region i, $seas$ is the season factor, $yield_{ijt}$ denotes the total yield of the jth kind of vegetable at period t in region i, $inflow_{ijt}$, $inflow_{iat}$ and $inflow_{ibt}$ denote the supply inflow of the jth kind of vegetable and its two main substitute vegetables, at period t in region i, respectively.

4.2 Planting structure and time optimization

After we determine the optimal price of the jth kind of vegetable at period t in region i, that is, p^*_{ijt}, the next step is to determine the planting area and time of each kind of vegetable, with the goal of maximizing total revenues of all greenhouses. Different kinds of vegetables have different growth periods, so the first constraint is to control the harvesting time of each kind of vegetable within its targeted period t. Moreover, different kinds of vegetables need different resource inputs such as greenhouse spaces, water, fertilizers, and labor which are often limited in greenhouses, so these resource constraints should be considered. Based on the above analysis, we present a planting structure and time optimization model, as below.

$$max \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T} area_{ijt} unityield_{ijt} p^*_{ijt} \quad (4)$$

s.t.

$$max\{growth_j\} \le 1 \quad (5)$$

$$area_{ijt} unityield_{ijt} + inflow_{ijt} \le D_{ijt} \quad (6)$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} area_{ijt} \le Space_t \quad (7)$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} area_{ijt} unitwater_{ijt} \le Water_t \quad (8)$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} area_{ijt} unitferti_{ijt} \le Ferti_t \quad (9)$$

$$\sum_{i=1}^{M}\sum_{j}^{N} area_{ijt} unitlabor_{ijt} \le Labor_t \quad (10)$$

$$\alpha \sum_{i=1}^{M}\sum_{j=1}^{N} area_{ijt} + \beta \sum_{i=1}^{M}\sum_{j=1}^{N} area_{ijt} unitwater_{ijt} + \gamma \sum_{i=1}^{M}\sum_{j=1}^{N} area_{ijt} unitferti_{ijt} + \eta \sum_{i=1}^{M}\sum_{j}^{N} area_{ijt} unitlabor_{ijt} \le Budg_t \quad (11)$$

In the objective function, $area_{ijt}$ is the decision variable in the operation, denoting the planting area of the jth kind of vegetable at period t in region i. M and N denote the total number of regions and the total kinds of vegetables, respectively. T is the operation duration. $unityield_{ijt}$ denotes the yield per unit area of the jth kind of vegetable at period t in region i. Thus, the objective means to maximize the total revenues of vegetables in all greenhouse regions during the whole operation duration.

Formula (5) guarantees that the harvesting time is during period t, where $growth_j$ is in terms of percentage, denoting the proportion of the growth period of the jth kind of vegetable over the tth duration; Formula (6) guarantees that the sum of yield and inflow of the jth kind of vegetable at period t in region i is not more than the corresponding demand; Formulas (7)–(10) are the resource constraints where $unitwater_{ijt}$, $unitferti_{ijt}$ and $unitlabor_{ijt}$, respectively, denote the water consumption, the fertilizer consumption, and the labor consumption at unit area for planting the jth kind of vegetable at period t in region i, and $Space_t$, $Water_t$, $Ferti_t$, $Labor_t$, respectively, denote the maximums of available greenhouse space, water, fertilizer and labor at period t; Formula (11) is the budget constraint where α, β, γ, and η denote the capital input unit greenhouse space, water, fertilizer and labor, respectively, and $Budg_t$ denotes the available total budget for all greenhouses at period t.

4.3 Water and fertilizer integrated control

In greenhouses, various techniques on water and fertilizer integrated control have been widely reported. The introduction of soil sensors can improve the intelligence of water and fertilizer integrated control systems. As Fig. 5 shows, soil sensors in greenhouses timely collect soil data including moisture, nutrient, electric conductivity, and PH value. According to the analysis on soil data, processing servers determine the moisture and nutrient status in current soil and compare the current status with the optimal status stored in servers. By the comparison, replenishment quantities of water and fertilizers can be obtained. Then, corresponding control commands are sent to PID (proportional-integral–differential) controllers in the water and fertilizer integrated control system. PID controllers open electromagnetic valves in corresponding proportions to supplement optimal water and fertilizers to greenhouses.

As we can see, the key operation here is to determine the optimal replenishment duration of water and fertilizers, which determines replenishment costs. The decision objective of water and fertilizer integrated control is to minimize total replenishment costs with limited resource constraints. A basic optimization model is formulated, as below.

$$\min \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{K}\sum_{t=1}^{T} duration_{ijt}unitreple_{ijkt}unitcost_{ijkt} + \sum_{i=1}^{M}\sum_{j}^{N}\sum_{t=1}^{T} duration_{ijt}unitpower_{it}p_{it}^{power} \tag{12}$$

s.t.

$$duration_{ijt} \le 1, \quad \forall i \in M, \quad \forall j \in N, \quad \forall t \in T \tag{13}$$

$$\sum_{j=1}^{N} duration_{ijt}unitpower_{it} \le Power_{it}, \quad \forall i \in M, \quad \forall t \in T \tag{14}$$

$$\sum_{j=1}^{N} duration_{ijt}unitreple_{ij1t} \le Water_{it}, \quad \forall i \in M, \quad \forall t \in T \tag{15}$$

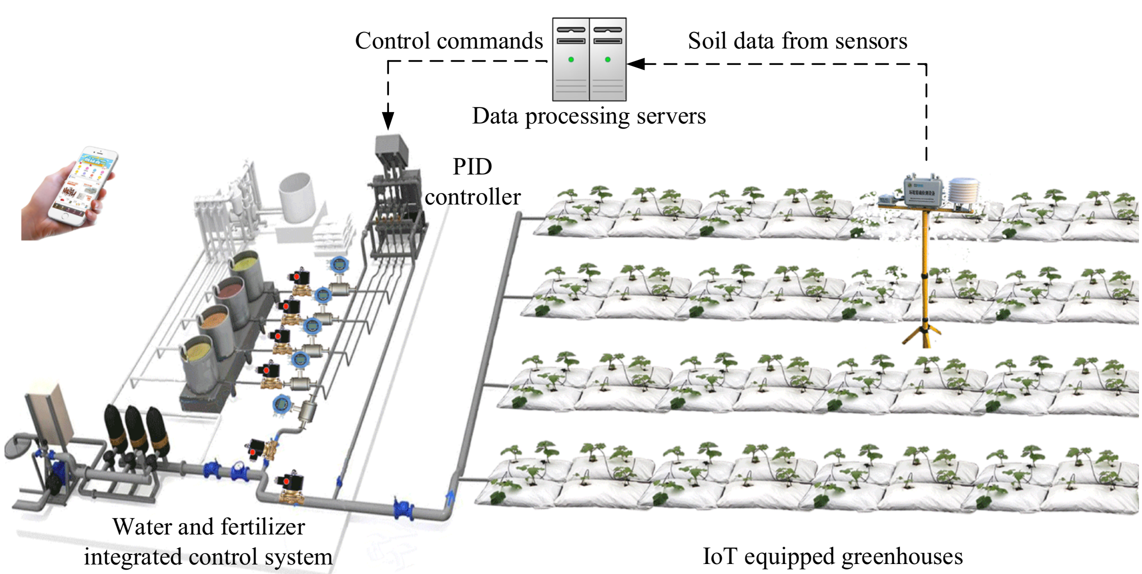

Fig. 5 A water and fertilizer integrated control system of IoT-equipped greenhouses

$$\sum_{j=1}^{N} duration_{ijt} unitreple_{ijkt} \le Fertilizer_{ikt}, \quad k = 2, 3, \ldots, K \tag{16}$$

In the objective function, $duration_{ijt}$ is the decision variable in the stage, denoting the replenishment duration for the jth kind of vegetable at period t in region i. K denotes the total kinds of fertilizers including water and fertilizers. $unitreple_{ijkt}$ and $unitcost_{ijkt}$ denote the replenishment quantity unit time and the unit cost of the kth kind of resources for the jth kind of vegetable at period t in region i. $unitpower_{it}$ and p_{it}^{power} denote the power consumption quantity unit time and the power fare at period t in region i, respectively. Thus, the objective is to minimize the total replenishment costs including water, fertilizers and power in all greenhouse regions during the whole operation duration.

Formula (13) guarantees that the replenishment duration is during period t; Constraint (14) guarantees the power consumption quantity in the replenishment is not more than the available power quantity $Power_{it}$ at period t in region i; Constraint (15) guarantees the water consumption quantity in the replenishment is not more than the available water quantity at period t in region i (denoted by $Water_{it}$), where $unitreple_{ij1t}$ denotes the water consumption quantity unit time; Constraint (16) guarantees the consumption quantity of the kth kind of fertilizer in the replenishment is not more than the available quantity of the kth kind of fertilizer at period t in region i (denoted by $Fertilizer_{ikt}$), where $unitreple_{ijkt}$ denotes the consumption quantity unit time of the kth kind of fertilizer.

4.4 Plant light supplement

Light is one of the necessary elements for photosynthesis, and the quality of light affects the yield and quality of crops, directly. Greenhouses provide suitable temperature and fertilizers to vegetables, but weaken the inside light situation which is about 30–70% of that at the outdoor. Thus, artificial light supplement becomes an inevitable choice of controllable greenhouses. In comparison with traditional light supplement techniques, IoT-equipped greenhouses can make more precise supplement with minimal costs and maximal quality. Figure 6 shows plant light supplement system of IoT-equipped greenhouses. Sensors in greenhouses collect and send related data including temperature, CO_2 and illumination intensity to data processing servers where supplement commands are determined by comparing current light situations with the optimal light situations required by vegetables. These supplement commands are sent to site controllers or farmers' remote phones. Then, LED (Light Emitting Diode) supplement lamps inside greenhouses are activated to make proper light supplement.

Two operation problems are involved in light supplement, that is, the network design of LED supplement lamps and the optimization of light supplement duration. More lamps and longer supplement durations than required will take more costs, and less lamps and shorter durations will impact the yields and quality of vegetables. Thus, these two operations have impact on the light supplement costs. The optimization of light supplement duration is similar with the decision of water and fertilizers replenishment duration, so here we only present a basic model for the network design of LED lamps, as below.

$$\min \sum_{i=1}^{M} \sum_{g=1}^{G_i} \sum_{b=1}^{B_{ig}} Lamp_{igb}(p^{lamp} + instalcosts) \tag{17}$$

s.t.

$$\sum_{b=1}^{B_{ig}} Lamp_{igb} cover \ge Area_{ig}, \quad \forall i \in M, \forall g \in G_i \tag{18}$$

$$\sum (coverdeg_c Block_{bc}) \ge Lamp_{igb}, \quad \forall c \in B_{ig} \tag{19}$$

$$coverdeg_b Dis_{bc} \ge Minidis \tag{20}$$

In the objective (17), $Lamp_{igb}$ is a binary decision variable which is 1 if a supplement lamp is set at the middle of the bth block of the gth greenhouse in region i and is 0 if not. G_i denotes the number of greenhouses in region i, B_{ig} denotes the number of blocks in the gth greenhouse in region i, p^{lamp} and $instalcosts$ denotes the price and installment costs of each LED lamp, respectively. Thus, the objective means to minimize the network implementation costs of LED supplement lamps.

Constraint (18) guarantees the maximal cover area of all LED lamps in greenhouse g is larger than the area of the gth greenhouse in region i (denoted by $Area_{ig}$), where $cover$ denotes the cover area of each LED lamp. Constraint (19) calculates the coverage degree of each lamp which reaches a sum of all coverage degrees, where $coverdeg_c \in \{0, 1\}$ denotes the coverage degree of the lamp and $Block_{bc}$ denotes the degree of coverage block c by the lamp on block b. Constraint (20) insures the minimal distance between two lamps, where Dis_{bc} denotes the distance between block b and c, and $Minidis$ denotes the minimal distance between two lamps.

4.5 Order-driven picking and packing

When vegetables can be harvested, another operation issue is to pick and pack vegetables based on online orders. In our business model, 18:00 pm is the start line to pick and pack vegetables required by consumers on the next day.

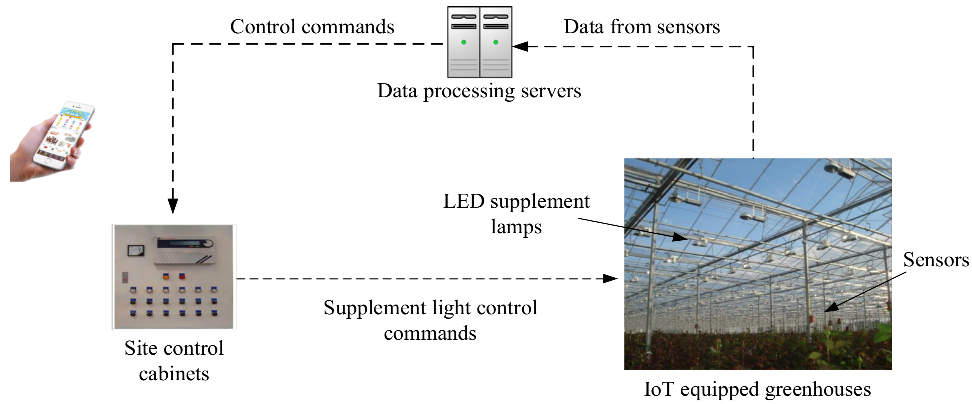

Fig. 6 A light supplement system of IoT-equipped greenhouses

After the start line, we download the orders and make corresponding picking and packing plans, as Fig. 7 shows. In addition, we can start our delivery only after all the picking, processing and packing works are finished. Thus, the objective of the picking and packing operation is to minimize the maximum completion time of all orders.

Based on the analysis on the practical processes, we formulate an order-driven picking and packing model, as below.

$$\min \max_{l\in\{1,2,\ldots,L\}} \{t_{il}^{enter} + t_{il}^{wait} + t_{il}^{pickpack}\} \tag{21}$$

s.t.

$$\sum_{i=1}^{M}\sum_{l=1}^{L} x_{ilo} = 1, \quad \forall o \in O \tag{22}$$

$$\sum_{i=1}^{M}\sum_{p=1}^{P} y_{ilp} = 1, \quad \forall p \in P \tag{23}$$

$$\sum_{i=1}^{M}\sum_{l=1}^{L} (y_{ilp}q_l) \le Q_p, \quad \forall p \in P \tag{24}$$

$$t_{il}^{enter} = t_{il}^{batch} + \min\{x_{ilo}t_{io}^{a}\}, \quad \forall i \in M, \quad \forall l \in L, \quad \forall o \in O \tag{25}$$

$$t_{il}^{wait} = t_{il}^{start} - t_{il}^{enter}, \quad \forall i \in M, \quad \forall l \in L \tag{26}$$

$$t_{il}^{start} \ge \max_{o\in\{1,2,\ldots,O\}} \{x_{ilo}t_{io}^{a}\}, \quad \forall i \in M, \forall l \in L, \forall o \in O \tag{27}$$

Objective (21) means to minimize the duration of picking and packing all considered consumers' orders on 1 day, where t_{il}^{enter}, t_{il}^{wait} and $t_{il}^{pickpack}$ denote the entering time, waiting time and pick-packing time of the l th batch of orders in region i. L denotes the maximal number of batches on each day.

Constraint (22) guarantees each order can be assigned to only one batch, where x_{ilo} is a binary variable, which is 1 if the oth order is assigned to the lth batch in region i and 0 if not, where O denotes the number of orders. Constraint (23) guarantees each batch can be assigned to only one picking farmer, where y_{ilp} is a binary variable, which is 1 if the lth batch is assigned to the pth farmer in region i and 0 if not, where P denotes the number of picking farmers. Formula (24) is the picking load constraint, where q_l denotes the load of each batch and Q_p denotes the maximal load of each picking farmer. Formulas (25) and (26) are used to calculate the entering time and waiting time of the lth batch, where t_{il}^{start} denotes the starting time of the lth batch in region i. Constraint (27) means a batch can be started

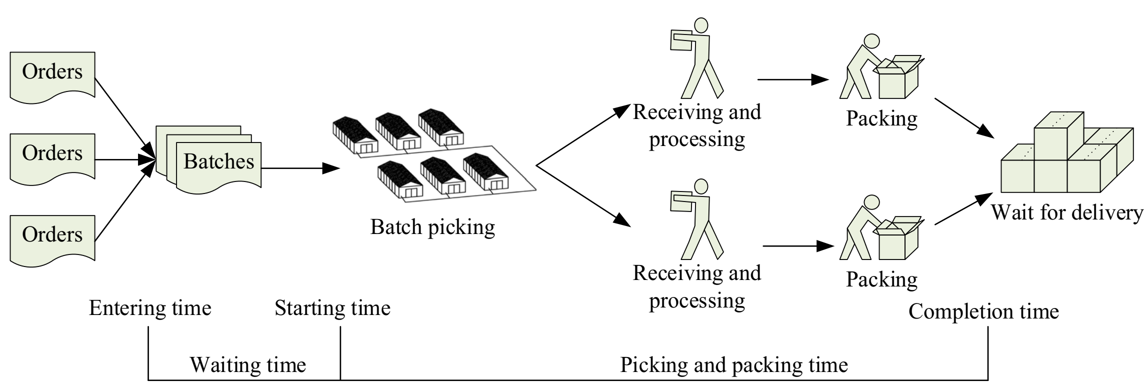

Fig. 7 An order-driven picking and packing problem of IoT-equipped greenhouses

only when all orders assigned to the batch are known, and t_{io}^{a} denotes the arrival time of the oth order in region i.

5 Conclusions

The popularity of IoT in agriculture is helpful to deal with the increasing food demands from the world. Both production and business in agriculture will be reshaped by IoT systems. Different kinds of agriculture face different impacts. In the work, we focus on greenhouse vegetables which are necessary for people's daily life. An IoT-based e-business model is presented for intelligent vegetable greenhouses. In details, incremental roles of related bodies in the business model are analyzed, key nodes in the basic process from greenhouses to consumers' dining-tables are recognized, and industry and value chains are specified. Then, we recognize and formulate five crucial operations in the IoT-based e-business model, that is, big-data-driven pricing, planting structure and time optimization, water and fertilizer integrated control, plant light supplement, and order-driven picking and packing. These operations have great impact on the costs and revenues of greenhouses, which should be well dealt with in the implementation of the IoT-based business model.

Although the IoT-based business model is promising for greenhouse farmers, more further studies are needed to make it come true. One is how to accelerate the IoT infrastructure construction in agriculture areas and promote Internet giants to provide IoT services. This process is critical but complicated, which will be analyzed in our future research. Another shortage of our work is that we just propose simple operation models of the five recognized operation issues. Any operation issue and its model could be extended to one future work.

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Compliance with ethical standards

Conflict of interest All the authors declare that they have no conflict of interest.

Ethical standards All the authors have read and have abided by the statement of ethical standards for manuscripts.

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