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A sustainable vegetable supply chain using plant factories in Taiwanese markets: A Nash–Cournot model

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ABSTRACT

Sustainable plant factory systems are able to provide steady and high-quality plants to markets while using less labor, water, nutrition, and pesticides. A plant factory is a controlled environment for plant production systems with artificial light, temperature, humidity, carbon dioxide, water supply, and cultivation solution. This paper focuses on the entry and competition of a plant factory supply chain in vegetable markets, using a Nash–Cournot model to simulate this competition. The Lagrangian multiplier method is used to derive KKT optimality conditions for the model. Combining the optimality conditions yields a linear complementarity problem (LCP), which is solved by GAMS and PATH. A case study of the plant factory supply chain in nine Taiwanese vegetable markets is presented. The research simulates the impact of the location of plant factories, number of firms, and different market demands. The results show that total production and profits of the plant factory supply chain increase as transportation costs decrease. In addition, the producer surplus, consumer surplus, and total surplus of the plant factory supply chain in Taiwanese markets improve when factories are located close to the markets. A sensitivity analysis is conducted which shows the impact of market share and production cost on the plant factory supply chain. While the case study focuses on the Taiwanese agricultural commodity production, the methodology and analysis procedures have generalizability to similar plant production industry problems in other contexts.

1. Introduction

1.1. Background

Plant factories are sustainable and environmental plants' growing systems because less water, nutrition, pesticides, and labor are consumed for plant cultivation. The systems control lighting, temperature, humidity, water, the concentration of carbon dioxide, etc. in order to create an artificial and efficient cultivation environment in an indoor space (Morimoto et al., 1995; Seginer and Ioslovich, 1999; Alfaro and Rabade, 2009; Winter Green Research, 2010; Ahumada and Villalobos, 2011). In plant factory systems, plants are grown consistently all year round by means of integrated high technology systems with efficient energy, natural, and labor resources input. Hence, plant factories are sustainable and artificially controlled environment systems which are able to stably produce high-quality vegetables.

Due to the high start-up cost of plant factories, the plant factory system is most often used to cultivate crops that have a high-profit return. High-profit vegetables cultivated by plant factory systems in Taiwan, Japan, and China include seedlings, herbs, fruits, and vegetables for consumers who are willing to pay the higher prices for these goods. In this paper, we analyze the entry of a plant factory supply chain in vegetable markets and, in addition, simulate competitive behavior among plant factories in these markets.

In this research, we analyze entry into vegetable markets and plant factory production competition in the markets by formulating a Nash–Cournot competition model (Hobbs, 2001; Gabriel and Fuller, 2010; Arnold and Minner, 2011; Chung et al., 2012; Shamir, 2012). Accordingly, KKT optimality conditions of the Nash–Cournot model are derived by applying the Lagrangian multiplier method. Combining KKT equations presents an LCP model. The LCP is a model that searches a real n-tulip vector variable, x, such that $(Ax+B)\geq 0$, $x\geq 0$, and $x^{\mathrm{T}}(Ax+B)=0$, where A is a real $n\times n$ matrix and B is a real n-tulip vector. When the perpendicular condition of $(Ax+B)$ and x is denoted by $\perp$, the LCP can be formulated as $[0\leq x]\perp[(Ax+B)\geq 0]$. In this paper, the LCP model is solved using the PATH solver and the GAMS. GAMS is an optimization modeling

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language for solving large, complex problems (Rosenthal, 2010). The PATH solver utilizes the most efficient algorithm for solving the LCP model (Ferris and Munson, 2000). Finally, we determine the market equilibrium solution of the Nash–Cournot model using both the GAMS and the PATH solver.

This paper is organized in the following manner. Section 2 discusses related literature. Section 3 formulates the Nash–Cournot competition model of plant factory production in vegetable markets. Then, KKT conditions are derived using the Lagrangian multiplier method. Accordingly, the mixed LCP model for plant factory systems is built and solved by the GAMS and PATH solver. Section 4 presents a case study in Taiwanese vegetable markets, and Section 5 presents the conclusions.

1.2. History of the plant factory systems in Taiwan

In Taiwan, plant factory technology is relatively new but has attracted interest from both the industry and academia. The first plant factory was established by Risecare Company in 2010, although they only provide a limited range of leafy vegetables. National Taiwan University installed a new plant factory in the campus in 2011, providing a facility for experts to conduct cultivation experiments in a clean and warm house environment. Furthermore, such techniques are also being tested by National Yilan University and National Chung Hsing University. The Taiwan Plant Factory Industry Development Association was established in May 2011, with approximately 40 organization members interested in plant factory technology and derived products. Most of these members form a part of the lighting technology, agricultural automatics, and agricultural cultivation technology industries, particularly the LED lighting system industry. The members intend extending their business into the field of plant factory cultivation systems, albeit using different business strategies. For example, Genesis Photonics Inc. and Everlight Electronics Co. Ltd, both LED technology companies, plan to have their own plant factories. Hon Hai Precision Ind. Co. Ltd. cooperates with the National Taiwan University for developing plant factory technology in vegetable cultivation. The current goal is to use the vegetables grown from their plant factories to satisfy the dietary need of their employees, a total of 1,300,000 people around the world. Their long-term goal is to commercialize their plant factory-grown vegetables and to obtain a 49% share of the market. Furthermore, Hon Hai Precision Ind. Co. Ltd. plans to cooperate with a university for developing vegetable cultivation technology for plant factories; the company has a long-term goal of obtaining a 49% share of the market for plant factory-grown business. Academic organizations have also contributed their resources to the development of plant factory technology. National Taiwan University, leading in plant factory technology in Taiwan, launches the products, including lettuce grown using the system, into the market. As a result of the high cost of plant factory technology, most investment in Taiwan is in the cultivation of plants with high economic value, such as lettuce, seedlings, or herbs used as raw material for the bio-technology industry. Some horticultural companies in Taiwan are planning to use plant factories to grow cut flowers. The high costs also mean that most plant factory vegetables target consumers who are willing to pay higher prices for these goods. There are also companies in Taiwan that plan to apply plant factory technology to urban horticulture. This will allow households in urban areas to use the factories and facilities to grow their vegetables without the need for soil, which is always in limited supply in these areas.

Five companies from the industries of lighting equipment, building planning, and material service have launched plant factories. The major products of Wang Yong Hydroponics Materials Co. Ltd. are lettuce, pak choi, Lactuca sativa Linn, and so on. Wang Yong Hydroponics Materials Co. Ltd. already has an enclosed environmental control plant factory. It also provides LED plant factory equipment, LED artificial light, and 3-D cultivation systems. Zhu Wang Agriculture Corporation focuses on the equipment, cultivation beds, and organic fertilizer, which are essential parts of the plant factory industry. Furthermore, Zhu Wang Agriculture Corporation operates as a direct selling store, assisting farmers to construct LED plant factories and accelerating the know-how transfer of the produce sales procedure in order to expand the market for LED plant lights. Ting Mao Development Co. Ltd focuses on LED plant-growing lighting, farm and commercial plant factories, medium and large plant factories, small plant factories, family-type layer plate gardens (customized), family balcony-style gardens, and desktop plant light kits as gifts. Zhan Ye International Co. Ltd. sells equipment for fully enclosed plant factories and growing chambers for home leisure planting. The main products grown in its plant factories are lettuce, pak choi, baby bok choy, spinach, crown daisy, coriander, and so on. Pacific Life Resort Development Co. Ltd. sells the vegetables grown from the plant factories. As mentioned earlier, the main crops cultivated by the plant factories of these five companies in Taiwan focus mainly on vegetables that have a high economic value.

The cultivation technology for plant factories has been developed in Taiwan and the relevant products are ready to launch to the market. However, most published research concentrates on technology development of the plant factory itself, while only limited reports focus on investment benefits. This paper analyzes the strategy for entering the plant factory industry. Technology alone is not enough to encourage investment in the industry. There also needs to be a market benefit to back up the total input (Kruseman and Bade, 1998).

2. Literature review

In this paper, we formulate Nash–Cournot and LCP models for analyzing the competitive interaction between plant factories in Taiwanese vegetable markets. Nash–Cournot and LCP models have been used in other research to simulate competition in economic and energy markets. Gabriel and Fuller (2010) formulated a stochastic LCP model to simulate quantity competition in uncertain energy markets. They modified the Benders decomposition method in order to solve the stochastic LCP model. Hobbs (2001) established a Nash–Cournot competition model to analyze bilateral and POOLCO electric power markets. This model examined the interactive behavior among power generation firms, transmission grid owners, and market clearing conditions in the energy markets. In addition, a Nash–Cournot model was built to determine the impact of biomass co-firing on market equilibrium in the Taiwanese power market (Hu et al., 2011).

With respect to plant factory production systems, optimization models and algorithms have been utilized for determining optimal controlling strategies (Tzilivakis et al. 2005; Pandey et al., 2007; McGuire, 2008; Amorim et al., 2012; Eben-Chaime et al., 2011; Flores and Villalobos, 2013). In addition, economic analyses have also been conducted to analyze plant factory production performance. Van Straten et al. (2000) analyzed optimal strategies of temperature, moisture, and carbon dioxide control for crop growing in greenhouses. Canakci and Akinci (2006) developed a dynamic optimal control model for greenhouse production in Turkey. Their model determined optimal strategies for cost and energy consumption for vegetable production in greenhouses. Jan de Wit Company analyzed strategies for the production and trading of lily flowers and built a linear programming model for decision support (Caixeta-Filho et al., 2002). Morimoto et al. (2003) established a dynamic optimization model to maintain water content in fruit during storage; their research used a neural