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CAPACITY RESERVATION FOR A DECENTRALIZED SUPPLY CHAIN UNDER RESOURCE COMPETITION: A GAME THEORETIC APPROACH

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ABSTRACT

This paper proposes a capacity reservation mechanism for a single-supplier and multi-manufacturer supply chain. The manufacturers first determine the production capacity they should reserve from the supplier, and then realize their reservations and place corresponding supplementary orders within a realization time window. The supplier builds its regular production capacity according to the reservations that have been received, and emergency production capacity for orders that exceed its regular capacity. Towards this end, we develop an analytical model to quantify the manufacturers' optimal capacity reservation quantities and realization times, as well as the supplier's optimal regular capacity. Given regular production capacity competition, a Cellular Automata (CA) simulation model is developed to resolve the analytical intractability of reservation realization time by modeling the manufacturers in an *N*-person game and identifying the convergence condition. Experiment results indicate that the proposed capacity reservation mechanism outperforms the traditional wholesale price contract in a decentralized supply chain.

1 INTRODUCTION

In a decentralized supply chain, delivery of high quality and low cost products to the end market on a timely manner is critical to keep or expand its market share. For those supply chains that require intensive labor involvement and face highly seasonal demand, expanding the production capacity while retaining low product cost during demand peak seasons has been recognized to be challenging. Those major challenges (e.g. uncertain seasonal demand and intensive labor cost) have been hindering the supply chain performance improvement in real practice. In addition, the double marginalization, which is a typical consequence of demand information asymmetry, has made it more difficult to determine the optimal production capacity. Solving this production capacity planning problem is especially critical for perishable product supply chains (e.g. grafted vegetable seedling supply chain considered in this paper) whose product market is usually price sensitive. Although information sharing has been widely studied, its applicability in real practice is still supply chain-dependent. This realistic concern is originated from a research project for reducing the grafted vegetable seedling cost within USA. In a typical grafted vegetable supply chain, our research is focused on two echelons, including a seedling supplier that produces grafted vegetable seedlings via intensive manual grafting, and several vegetable producers that seasonally purchase grafted seedlings according to certain planting schedule and plant vegetables for supplying the end market (e.g. grocery stores). During demand peak seasons (normally in spring of each year), the biggest challenge for the seedling supplier to achieve low seedling cost is to form skilled grafting capacity rather than employing a large number of unskilled workers whose low efficiency (e.g.

low grafting speed and quality ratio) substantially increases the seedling cost. It is even possible that the labor market, sometimes, is unable to provide enough unskilled workers within a short time. Therefore, to form cost effective grafting capacity prior to the demand peak period and secure the labor supply, the seedling supplier needs to know the vegetable producers' order quantity as early as possible. This requirement, however, inevitably increases vegetable producers' demand forecasting errors. Therefore, a coordination mechanism between the seedling supplier and the vegetable producers is needed to allow the vegetable producers to reveal as much demand information as possible prior to the determination of the supplier's production capacity. Accordingly, the optimal decisions (e.g. production capacity and order quantity) for both the seedling supplier and the vegetable producers need to be quantified, respectively.

In this paper, we propose a capacity reservation mechanism for a single-supplier (e.g. seedling supplier) and multi-manufacturer (e.g. vegetable producer) supply chain to allow the supplier to build its capacity early while improve the profit of the entire supply chain. In the past decades, many literature works have contributed to applying capacity reservation to coordinating various types of supply chains. For instance, Jain and Silver (1995) studied a single product capacity reservation problem in a single-buyer and single-supplier supply chain. They proposed an algorithm for finding the buyer's optimal reservation quantity and the supplier's capacity. Cachon and Lariviere (1999) were focused on capacity allocation mechanism when the retailers' orders exceed the supplier's existing capacity via game theory. They proposed an allocation mechanism that induces retailers to reveal the true demand information such that the entire supply chain can be better off. Erkoc and Wu (2005) proposed two types of capacity reservation mechanisms for a single-supplier and single-manufacturer supply chain: partial payment deduction and reservation with cost sharing. They first showed that in the cases of voluntary contract compliance and partial demand information updating, the equilibrium decisions are distinct from the forced compliance case. Then they demonstrated that supply chain coordination can be achieved with buy-back agreements. Özer and Wei (2006) compared the capacity reservation mechanism with the advance purchase mechanism, and demonstrated that via the capacity reservation mechanism the supplier can detect the manufacturer's demand forecast information. Their analysis showed that the supply chain efficiency is determined by the degree of demand forecast information asymmetry and the risk-adjusted profit margin. Mathur and Shah (2008) proposed a price compliance regime, where the supply chain parties (e.g. the supplier and its retailer) comply on the prices rather than the quantity to be ordered. They also included in the model that the supplier and its retailer need to pay penalty for short supply or short orders, respectively. Pezeshki et al. (2013) studied a capacity reservation mechanism for a single period two-echelon supply chain. They proposed coordinating contracts for several cases with respect to full/partial demand information updating as well as forced/voluntary compliance regimes. One major contribution of their paper is that they modeled the supplier's capacity as the combination of production rate and production time rather than total production quantity. Park and Kim (2014) was focused on capacity reservation mechanisms for a single-manufacturer and multi-supplier supply chain. They proposed a rolling-horizon implementation strategy and linear programming model to tackle multi-period replenishment decision making problem. Li et al. (2014) studied a capacity reservation contract for a single period two-echelon supply chain. Their major contribution is to derive the closed form solution for the supplier's capacity decision and the retailer's procurement decision given the demand is uniformly distributed. Asian and Nie (2014) first studied a capacity reservation contract for a two-echelon supply chain in which a retailer places orders from an unreliable major supplier at a cheaper price and reserves capacities from a reliable backup supplier at a higher price. They provided the retailer's optimal reservation decision, the backup supplier's optimal production capacity decision, as well as the coordination conditions for the supply chain. Wu et al. (2014) studied a capacity reservation contract between integrated device manufacturers (i.e. buyers) and foundries (i.e. sellers). Given that the integrated device manufacturers also possess production capacity, they found that if their capacity investment risk is not extremely low, there exist coordinating capacity reservation contracts. Capacity reservation mechanism is also widely used together with spot market as an operation risk hedging for high spot market prices. For example, Serel (2007) studied a multi-period dual sourcing (i.e. capacity reservation and spot market) problem by considering a price dependent spot market capacity. They derived the optimal inventory policy for the manufacturer. For the similar problem setting where the spot market capacity is infinite instead, Inderfurth, Kelle and Kleber (2013) adopted the dynamic programming approach to derive the structure of the manufacturer's optimal purchasing policy. They also proposed a heuristic to search for the optimal procurement policy for each period.

Under the capacity reservation mechanism proposed in this paper, the manufacturers pay fees for reserving the supplier's production capacity prior to their regular ordering times based on their demand forecasting. Based on the reservations that have been received, the supplier is able to build regular production capacity at a lower cost rate. Finally, the manufacturers determine the quantity of reservation to realize before or after the demand from downstream is revealed. In the proposed mechanism, we allow the manufacturers to place supplementary orders if the reserved capacity is insufficient to meet the demand from their downstream, and the supplier to build emergency production capacity to meet the manufacturers' orders that exceed its existing regular capacity. Most of the studies reviewed in the previous paragraph were focused on a single-manufacturer and single-supplier structure or single-manufacturer and dual-sourcing structure, which do not apply to our supply chain structure (i.e. single-supplier and multi-manufacturer). In reality, it is common for a supplier to have multiple customers and therefore the capacity planning needs to include multiple order sources. In addition, those studies have assumed that the capacity reservation is always realized when the demand is fully revealed, which may not be the case when capacity competition exists or the manufacturers adopt make-to-order policy. Due to the research gap between the existing literatures and our problem, this paper contributes to the literature in the following aspects. (1) We allow the manufacturers to realize their reservations before the demand from their downstream is fully revealed for competing for the supplier's remaining regular capacity; (2) for the single-supplier and single-manufacturer structure, we derive closed form solutions to the supplier's optimal regular capacity and manufacturer's capacity reservation quantity under the proposed mechanism, as well as the supplier's optimal capacity under centralized supply chain; (3) for the single-supplier and multi-manufacturer structure where the optimal reservation realization time is analytically intractable, we model the manufacturers' decision makings as an *N*-person game, and develop a Cellular Automata (CA) simulation model to identify the convergence condition of the manufacturers' reservation realization times.

The rest of paper is organized as follows. The supply chain configuration and the proposed capacity reservation mechanism are described in Section 2. The proposed mechanism is modeled for a single-supplier and single-manufacturer supply chain, and a single-supplier and multi-manufacturer supply chain in Sections 3 and 4, respectively. In Section 5, the CA simulation model is presented, and the experiment is conducted in Section 6. Conclusions and future extensions are discussed in Section 7.

2 SUPPLY CHAIN DESCRIPTION

In the supply chain considered in this paper, the manufacturers face seasonal demand for a single type of product from their downstream customers. In order to produce the product, the manufacturers order one type of components from the same supplier. For the supplier, it determines its regular production capacity before firm orders from the manufacturers are received, and then builds emergency capacity to fulfill orders that exceed its regular capacity. The proposed capacity reservation mechanism can be explained via Figure 1. At time a_1, each manufacturer reserves RQ_k^i (see Table 1) units of component production capacity from the supplier at unit price r based on their demand (for the product) forecasting. Then the supplier determines the regular capacity as Cap^i based on the reservations that have been received, and builds it at unit cost c_r during $a_1 - a_2$. At time a_3, the demand D_k for the product is completely revealed to each manufacturer. The manufacturers can realize their reservations any time between a_2 and a_3, meaning that a manufacturer can commit its order quantity even before knowing the actual demand. In this case, the individual manufacturer may experience overage or underage cost when the demand from its downstream is fully revealed. Each manufacturer can purchase up to RQ_k^i units of components (i.e. reservation quantity) at unit cost w in addition to r. Since the actual demand may exceed the reserved capacity RQ_k^i, each manufacturer can place supplementary order SQ_k^i. If the total committed orders (i.e. realized reservations and supplementary orders) exceed the supplier's regular capacity, the emergency capacity can be built at unit cost c_e ($c_e > c_r$) to fulfill the excessive orders. The emergency capacity is determined at time a_3, after all the orders (realized reservations and supplementary orders) are received. The remaining regular capacity after fulfilling reservations is assigned to supplementary orders based on the First Come First Serve (FCFS) basis. The unit price for supplementary order could be s_r ($s_r > r + w$) for the quantity that fulfilled by the regular capacity, or s_e ($s_e > s_r$ and $r + w - c_r > s_e - c_e$) for the quantity that has to be fulfilled by the emergency capacity.

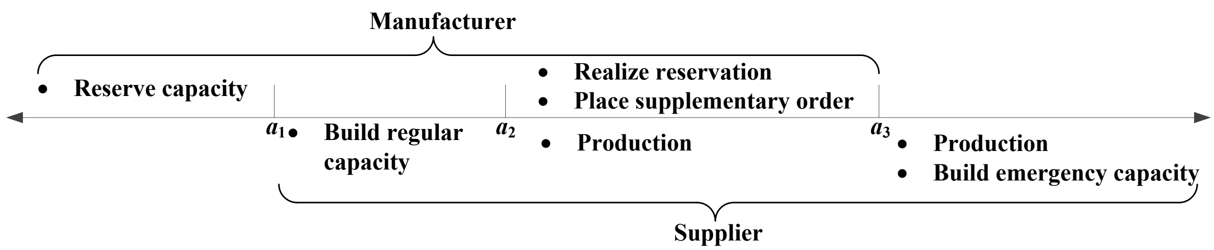


Figure 1: Interactions between a supplier and a manufacturer under capacity reservation.

In this paper, the following assumptions are made. For the supplier, we only consider the capacity planning during the peak season when temporary capacity (e.g. seasonal workers) needs to be built, and the existing capacity is not included in the model. The detailed production schedule for the supplier is neglected in this paper since long production cycle time requires concurrent production. For the manufacturers, we assume they are homogeneous in terms of product sale price and production cost. This assumption is reasonable for products in the mature stage, in which the sale price is determined by the market and production technologies are similar for different manufacturers. We further assume that the manufacturers have their own loyal customers, and have no competition between each other. That is because our paper is focused on the capacity planning and ordering decisions rather than market competitions among manufacturers. However, they may compete for supplier's regular capacity while placing supplementary orders for lower cost. Transportation cost and time between the supplier and manufacturers are negligible relative to the production cost and cycle time.

We assume that the manufacturers have independent demand from their downstream market. The demand for the product is stochastic, and has mean of μ_k and standard deviation of $\mu_k\theta(T)$, where $\theta(T) = (a_3 - T) / \left[\alpha(a_3 - a_1)\right]$. The expression of the demand standard deviation infers that the demand uncertainty decreases as time approaches a_3 and α is a coefficient that determines how fast the uncertainty decreases. We assume that $\theta(T)$ is also known to the supplier.

Table 1: Parameters for supply chain modeling.

Notation	Description	Notation	Description
i	Model index, *a*/*b*: decentralized/centralized single-supplier and single-manufacturer model *c*/*d*: decentralized/centralized single-supplier and multi-manufacturer model	T_k^i	Manufacturer *k*'s time to realize reservation and order supplementary order
k	Manufacturer index	w	Reservation realization price per unit
c_r	Supplier's regular capacity construction cost per unit	p	Manufacturer's product sale price per unit
c_e	Supplier's emergency capacity construction cost per unit	D_k	Demand for manufacturer *k*
c_s	Supplier's production cost per unit	Cap^i	Supplier's regular capacity
c_m	Manufacturer's production cost per unit	RQ_k^i	Manufacturer *k*'s reservation quantity
s_r	Supplementary order price per unit for regular capacity	SQ_k^i	Manufacturer *k*'s supplementary order quantity
s_e	Supplementary order price per unit for emergency capacity	WQ_k^i	Manufacturer *k*'s reservation realization quantity ($WQ_k^i \le RQ_k^i$)
r	Capacity reservation price per unit		

3 A SINGLE-SUPPLIER AND SINGLE-MANUFACTURER STRUCTURE

3.1 Optimality for a Decentralized Supply Chain

Since only one manufacturer is modeled in this supply chain structure, we index it as 1 through Section 3. The manufacturer reserves the capacity at time a_1 and the corresponding standard deviation of its demand is $\mu_1\theta(a_1)$. Then the optimal reservation quantity considering supplementary order can be obtained by solving a newsvendor problem defined in Equations (1) and (2). The optimal solution is given in Equation (3).

$$\max_{RQ_1^a} \pi_M^a \tag{1}$$

$$\pi_M^a = \int_0^{RQ_1^a} (p-w-c_m)xf_1(x)dx + \int_{RQ_1^a}^{\infty} (p-s_r-c_m)(x-RQ_1^a)f_1(x)dx + \int_{RQ_1^a}^{\infty} (p-w-c_m)RQ_1^a f_1(x)dx - rRQ_1^a \tag{2}$$

$$RQ_1^{a*} = F_1^{-1}\left(\frac{s_r-r-w}{s_r-w}\right) \tag{3}$$

where $f_1(\cdot)$ and $F_1(\cdot)$ are probability density and cumulative distribution functions with mean μ_1 and standard deviation $\mu_1\theta(a_1)$, respectively. Based on Equation (3), the supplier would take it as the mean of the manufacturer's stochastic demand.

Then the supplier's optimal capacity can be obtained by solving a newsvendor problem defined in Equation (4) and (5). The optimal solution is given in Equation (6).

$$\max_{Cap^a} \pi_S^a \tag{4}$$

$$\begin{aligned}\pi_S^a = &\int_0^{RQ_1^{a*}} (w-c_s)xg(x)dx + \int_{RQ_1^{a*}}^{Cap^a} [(w-c_s)RQ_1^{a*} + (s_r - c_s)(x - RQ_1^{a*})]g(x)dx + rRQ_1^{a*} - c_r Cap^a \\ &+ \int_{Cap^a}^{\infty} [(s_r - c_s)(Cap^a - RQ_1^{a*}) + (w-c_s)RQ_1^{a*} + (s_e - c_e - c_s)(x - Cap^a)]g(x)dx\end{aligned} \tag{5}$$

$$Cap^{a*} = G^{-1}\left(\frac{s_r + c_e - s_e - c_r}{s_r + c_e - s_e}\right) \tag{6}$$

where $g(\cdot)$ and $G(\cdot)$ are probability density and cumulative distribution functions with mean RQ_1^{a*} and standard deviation $RQ_1^{a*}\theta(a_1)$.

3.2 Optimality for a Centralized Supply Chain

In the centralized supply chain, the supplier and the manufacturer can be considered as one party (e.g. a supplier) facing the external demand. Thus, the optimal regular capacity can be obtained by solving a newsvendor problem defined in Equations (7) and (8). The optimal solution is given in Equation (9).

$$\max_{Cap^b > 0} \pi^b \tag{7}$$

$$\pi^b = \int_0^{Cap^b} \left[(p-c_s)x - c_r Cap^b\right] f_1(x)dx + \int_{Cap^b}^{\infty} \left[(p - c_e - c_s)(x - Cap^b) + (p - c_r - c_s)Cap^b\right] f_1(x)xdx \tag{8}$$

$$Cap^{b*} = F_1^{-1}\left(\frac{c_e - c_r}{c_e}\right) \tag{9}$$

It is observed that the optimal regular capacity is determined by both emergency and regular capacity construction cost rates.

4 A SINGLE-SUPPLIER AND MULTI-MANUFACTURER STRUCTURE

4.1 Optimality for Decentralized Supply Chain

In this structure, manufacturer *k* needs to consider other manufacturers' reservation realization times in order to place supplementary order (if necessary) at the regular capacity rate (since the regular capacity is limited and acquired on the FCFS basis). For the reservation quantity, due to the demand independency each manufacturer still follows the same decision as in the single-supplier and single-manufacturer structure , which is $RQ_k^{c*} = F_k^{-1}\left(\frac{s_r - r - w}{s_r - w}\right)$. To determine the optimal reservation realization time, each manufacturer needs to take into account the supplier's remaining regular capacity and the demand uncertainty at the particular decision making time point. At time a_3 (the demand is completely revealed), manufacturer *k*'s profit is

$$\pi_k^c = (p - c_m)D_k - rRQ_k^{c*} - s_r L(S_k^c) - s_e[S_k^c - L(S_k^c)] \tag{10}$$

and

$$L(S_k^c) = \begin{cases} S_k^c & \text{if } Cap^c \geq S_k^c \\ Cap^c & \text{otherwise} \end{cases} \tag{11}$$

where $S_k^c = \left[D_k - RQ_k^{c*}\right]^+$. In Equation (10), the first term is the total revenue, and the rest are reservation cost, supplementary order cost for regular capacity and supplementary order cost for emergency capacity, respectively.

When manufacturer *k* realizes its reservation earlier than time a_3, then its expected profit is

$$\pi_k^c(WQ_k^c, T_k^c) = \begin{cases} \int_0^{WQ_k^c} (p - c_m) f_k(x, T_k^c) x dx - rRQ_k^{c*} - wWQ_k^c & \text{if } WQ_k^c \le RQ_k^{c*} \\ \int_0^{WQ_k^c} (p - c_m) f_k(x, T_k^c) x dx - (r + w) RQ_k^{c*} - s_r L(SQ_k^c) - s_e [SQ_k^c - L(SQ_k^c)] & \text{otherwise} \end{cases} \quad (12)$$

where $a_2 \le T_k^c \le a_3$, $f_k(x, T_k^c)$ is the probability density function with mean μ_k and standard deviation $\mu_k \theta(T_k^c)$. Note that if no regular capacity is available at the moment a manufacturer plans to realize its reservation , the manufacturer will choose to continue to wait until time a_3. That is because taking early action in that situation (e.g. without low purchase rate for regular capacity) provides no benefit for the manufacturer. For the case where the supplier has remaining regular capacity, a manufacturer determines the order quantity as follows.

$$SQ_k^c = \begin{cases} \tilde{F}_k^{-1}\left(\frac{p - c_m - s_r}{p}\right) & \text{if } CapR^c(T_k^c) \ge \tilde{F}_k^{-1}\left(\frac{p - c_m - s_r}{p}\right) \\ CapR^c(T_k^c) + \hat{F}_k^{-1}\left(\frac{p - c_m - s_e}{p}\right) & \text{otherwise} \end{cases} \quad (13)$$

where $\tilde{F}_k(\cdot)$ is a cumulative distribution function with mean of $\mu_k - WQ_k^c$ and standard deviation of $\theta(T_k^c)(\mu_k - WQ_k^c)$, $\hat{F}_k(\cdot)$ is a cumulative distribution function with mean of $\mu_k - WQ_k^c - CapR^c(T_k^c)$ and standard deviation of $\theta(T_k^c)[\mu_k - WQ_k^c - CapR^c(T_k^c)]$, and $CapR^c(T_k^c)$ is the remaining regular capacity.

For the supplier, the only available information for planning the regular capacity is the quantity of reservations that have been received. Therefore, the supplier's optimal regular capacity is

$$Cap^{c*} = \tilde{G}^{-1}\left(\frac{c_e - c_r}{c_e}\right) \quad (14)$$

where $\tilde{G}(\cdot)$ is a cumulative distribution function with mean of $\sum_{k=1}^{N} RQ_k^{c*}$ and standard deviation of $\sqrt{\sum_{k=1}^{N} [RQ_k^{c*} \theta(a_1)]^2}$.

4.2 Optimality for Centralized Supply Chain

In the centralized supply chain, the mean of the total demand distribution (i.e. $F(\cdot)$) can be expressed by summating the means of demand for each manufacturer, which is $\sum_{k=1}^{N} \mu_k$. The corresponding standard deviation is $\sqrt{\sum_{k=1}^{N} [\mu_k \theta(a_1)]^2}$. Similar to the previous single-supplier and single-manufacturer structure, the supplier's optimal regular capacity can be obtained by solving the newsvendor problem defined in Equations (15) and (16). The corresponding optimal solution is given in Equation (17)

$$\max_{Cap^d} \pi^d \tag{15}$$

$$\pi^d = \int_0^{Cap^d} \left[(p-c_s)x - c_r Cap^d \right] f(x)dx + \int_{Cap^d}^{\infty} \left[(p-c_e-c_s)(x-Cap^d) + (p-c_r-c_s)Cap^d \right] f(x)xdx \tag{16}$$

$$Cap^{d*} = F^{-1}\left(\frac{c_e - c_r}{c_e} \right) \tag{17}$$

5 CELLULAR AUTOMATA SIMULATION

In order to identify the manufacturer's reservation realization time, we model the manufacturers' interactions in a N-person game. We develop a CA simulation model for the N-person game by considering the effect of each manufacturer's reservation realization time on its own and other manufacturers' profits as modeled in Equation (12). The simulation model is developed in the agent-based simulation software NetLogo. In the developed simulation model, each manufacturer is modeled as an agent that has exact eight neighbors to interact with via reservation realization time decision. Each manufacturer's neighbors represent other manufacturers that also order from the same supplier. The payoff is the profit as defined in Equation (12). In this paper, we study two types of personalities for the agents, which are greedy and Pavlovian, respectively. Greedy personality has been adopted in studying supply chain members' behaviors and decision making (e.g. Sen, Saha and Banerjee 2005). A greedy agent imitates the neighbor with highest payoff over iterations (Szilagyi 2003). For a Pavlovian agent, its probability of making a certain decision (i.e. reservation realization time in this paper) changes by an amount proportional to the payoff it receives from the environment. Pavlovian personality is originated from Pavlov's experiments and Thorndike's law (Thorndike 1911). That is, if a decision is followed by a satisfactory payoff, then the tendency of the agent to make the same decision is reinforced. Since such realistic personality has not been widely studied in the supply chain area, modeling supply chain decision makers as Pavlovian agents is necessary.

The simulation logic is developed as follows. The simulation evolves over iterations, and all the agents only interact with their neighbors. One iteration can be considered as one decision making period (e.g. one year) in real practice. An agent's reservation quantity is determined via Equation (3), and the supplier's regular capacity for each neighborhood (which contains nine agents) is determined via Equation (14). The profits of agents are determined via Equation (12). If the realization time is smaller than a_3, an agent determines the supplement order quantity via Equation (13).

For greedy agents, if no other neighbor agents have better profit at current iteration, it will repeat its current reservation realization time in the next iteration. For a Pavlovian agent k, we use $s_k(iter)$ to denote its tendency of increasing or decreasing the reservation realization time at iteration *iter* (Zhao, Szidarovszky, and Szilagyi 2008). $s_k(iter)$ is between 0 and 1, and moves over iterations towards direction

$$h_k(iter+1) = \begin{cases} \alpha(\pi_k^i(iter) - \pi_k^i(iter-1)) & if\ T_k^i(iter) \geq T_k^i(iter-1) \\ -\beta(\pi_k^i(iter) - \pi_k^i(iter-1)) & otherwise \end{cases} \tag{18}$$

where α and β are coefficients.

6 EXPERIMENT

In the experiment, the data specified in Table 2 were used for deriving the optimal solutions (i.e. the supplier's regular capacity and manufacturers' reservation quantities) and simulation inputs. In addition, the simulation model contains 121 agents. It is necessary to point out that the simulation needs to have a certain number of agents to overcome the effect of randomness (e.g. initial distribution of realization times and Pavlovian agents' decisions) on the convergence. Based on the pilot experiments, when the number of agents is small (e.g. nine agents), the results from different simulation runs gave different convergences. When the number of agents reaches 121, the convergence results from the same experiment setting become stable.

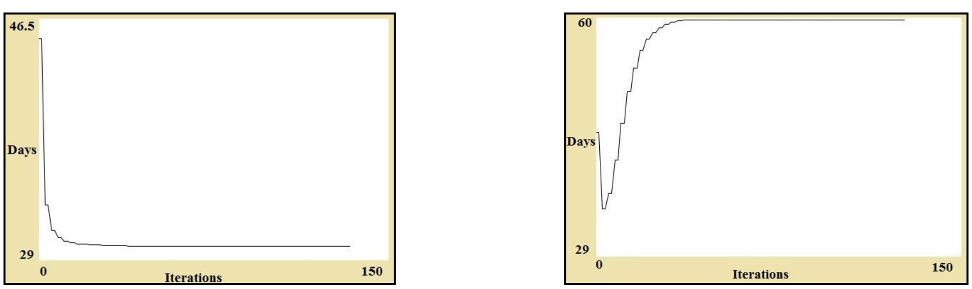
Table 2: Experiment parameters.

μ_k (unit)	a_1 (day)	a_2 (day)	a_3 (day)	r (\$/unit)	w (\$/unit)	s_r (\$/unit)
10000	0	30	60	1	9	12
s_e (\$/unit)	c_m (\$/unit)	p (\$/unit)	c_r (\$/unit)	c_e (\$/unit)	c_s (\$/unit)	
18	2	22	4	14.5	3	

In the following discussion, we denote the reservation realization time as T by dropping the superscript and subscript. For each experiment setting with respect to the ratio of agents initially with $T = 60$, we conducted 10 simulation runs.

6.1 Greedy Agents

We first modeled the manufacturers as greedy agents who imitate the decision (i.e. reservation realization time) of neighbors that receive the highest profit. In addition, we randomly assigned the initial value of reservation realization time to each agent, and terminated each simulation run until the average reservation realization time converged. Panel *a* of Figure 2 depicts the convergence result for no agents having initial reservation realization time of a_3, and Panel *b* depicts the result for 1% of agents having initial reservation realization time of a_3. Panel *a* shows that the reservation realization time converged to $T = 30$, which is the lower bound (i.e. a_2) of the realization time window. The result in Panel *a* implies that agents compete for the limited resource (i.e. the supplier's regular capacity) over iterations, and eventually they all realize their reservations at the earliest time possible (i.e. $T = 30$). Panel *b* shows that the reservation realization time converged to $T = 60$, which is the upper bound (i.e. a_3) of the realization time window. For further investigation, we selected 2%, 3%, 4%, 5%, 10%, 20%, 40%, 60%, 80% and 99% as the ratio of agents with initial reservation realization time of a_3 for experiments, and found that in all cases the reservation realization time converged to $T = 60$. This is because realizing the reservation at a_3 gives the highest profit when the supplier has enough regular capacity (see Section 6.3 for detailed discussion). Even though the supplier's regular capacity is limited (less than the total quantity of nine agents' supplementary orders), there exists at least one agent (with $T = 60$) that receives the highest profit. Thus the rest of agents will imitate its decision (i.e. $T = 60$) gradually as shown in Panel *b*.

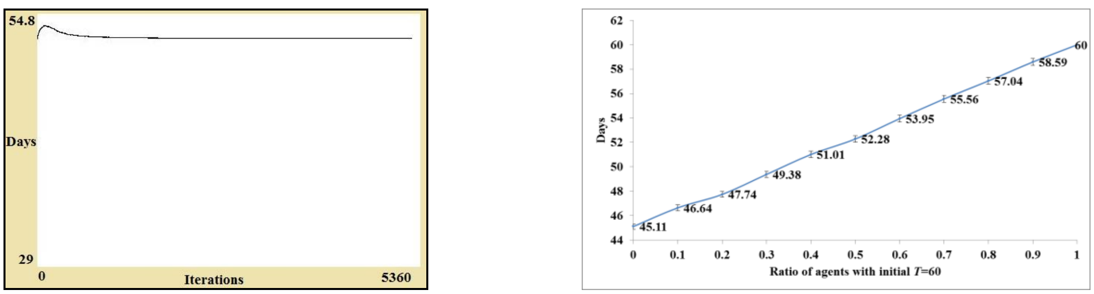


Panel a: No agent with initial $T = 60$ Panel b: 1% agents with initial $T = 60$

Figure 2: Convergence of reservation realization time for greedy agents.

6.2 Pavlovian Agents

Similar to the experiments for greedy agents, we selected 10 values (0% to 100%) for the ratio of agents with initial reservation realization time $T = 60$ for investigating the convergence result. In addition, we randomly assigned the initial value of reservation realization time to each agent, and terminated each simulation run until the average reservation realization time converged. Panel *a* of Figure 3 shows the average reservation realization time over 5000 iterations when 50% of agents are with initial $T = 60$. All the experiments, except for ratio of 100%, had the similar convergence path as shown in Panel *a*, which is that the average reservation realization time climbed up at the initial phase of the simulation while gradually declined to the convergence value. Panel *b* depicts the specific convergence times for different ratios. Different from the experiments for greedy agents, Pavlovian agents converge to different times if start with different ratios. Another observation is that when the ratio is 100%, the reservation realization time always converges to $T = 60$, while it oscillates around a certain value when the ratio is less than 100% (depicted by error bars). These observations imply that Pavlovian agents can always form local stability within the neighborhood, even though they may have better option (e.g. delay the reservation realization time). Once the stability is formed, each agent will repeat its decision around the convergence.



Panel a: 50% of agents with initial $T = 60$ Panel b: Convergence of reservation realization time

Figure 3: Convergence of Pavlovian agents' reservation realization times.

6.3 Supply Chain Profit Analysis

After identifying the reservation realization time, we are able to quantify the supplier's and manufacturers' profits via using the proposed capacity reservation mechanism.

We first designed five scenarios, including *S*1 as the centralized supply chain, *S*2 as the decentralized supply chain using conventional wholesale price contract, and *S*3-*S*5 as decentralized supply chain using the capacity reservation mechanism with $T = 60$, 58 and 56, respectively. The supply chain consists of one supplier and nine manufacturers (i.e. one neighborhood in the CA simulation model). As shown in Figure 4, the centralized supply chain (*S*1) achieved the highest profit, which is the optimum that the supply chain can achieve. Even though *S*3-*S*4 did not achieve the optimum (because it is decentralized supply chain with asymmetric information), all of them outperformed *S*2, meaning that the proposed capacity reservation mechanism can improve the supply chain performance.

We further investigated how the reservation realization time affects the supplier's and manufacturer's profits, respectively. Figure 5 shows the manufacturer's profit under different reservation realization times when the supplier has sufficient regular capacity for supplementary order. The result implies that a manufacturer would lose profit by advancing its reservation realization time because of larger demand uncertainty. Interestingly for the supplier (Figure 6), early reservation realization time is also harmful because the manufacturers may lose some demand by committing their total order quantity before the demand is revealed.

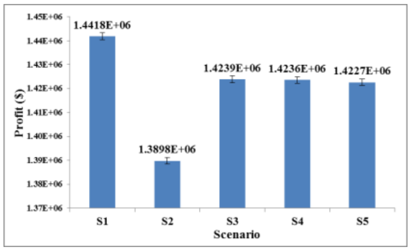


Figure 4: Supply chain's profit.

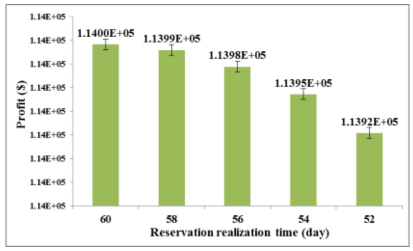


Figure 5: Manufacturer's profit.

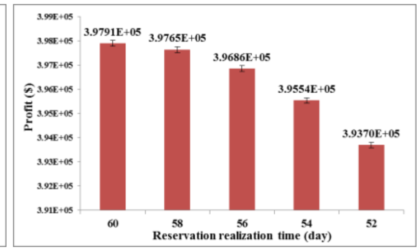


Figure 6: Supplier's profit.

7 CONCLUSION

In this paper, we have proposed a capacity reservation mechanism for a single-supplier and multi-manufacturer supply chain. The proposed mechanism allows the manufacturers to reserve production capacity from the supplier and realize the reservation within a certain realization time window. The supplier benefits from the reservations for more demand information and thus better capacity planning decision. The paper has developed an analytical model to quantify the manufacturers' optimal capacity reservation quantities and the supplier's optimal regular capacity. To address the analytical intractability of the manufacturers' reservation realization times, a Cellular Automata (CA) simulation model has been developed where the manufacturers are modeled as agents. Two types of personalities, greedy and Pavlovian, are considered to define the manufacturers' decision making behaviors and their interactions. The experiment results indicate that (1) greedy agents (i.e. manufacturers) always realize the reservation at two bounds of the realization time window; (2) Pavlovian agents' reservation realization times converge differently depending on agents' initial realization times; (3) the proposed capacity reservation mechanism outperforms the conventional wholesale price contract; and (4) when the supplier has enough regular capacity, postponement of reservation realization time is beneficial to both the supplier and the manufacturers. Our future extension is to introduce supplier substitution (i.e. multi-supplier) and investigate the convergence of the reservation realization under mixed personality (e.g. partial greedy and partial Pavlovian).

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