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Impacts of Order Cycle Time on the Bullwhip Effect: A Numerical Study

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Abstract

The bullwhip effect phenomenon refers to the amplification of demand variability as movingaway from the end customers to the suppliers in a supply chain. This research is concerned with the impacts of order cycle time on the bullwhip effect by considering its four major causes, i.e., demand forecast, price fluctuation, anticipation of shortages, andorder batching. Considering a two-echelon supply chain, fournumerical examples are developed where a multi-period inventory system with a periodic review policy is used.In each order cycle, a replenishment is initiated to raise the inventory to the order-up-to level, and the variance ratio of the manufacturer order to the market demand is calculated. Our results show that order cycle time reduction could counterattack four major causes of the bullwhip effect at the same time.

Keywords: Bullwhip effect; order cycle time; supply chain management; variance amplification.

1. Introduction

The bullwhip effectphenomenon refers to the amplification of demand variability as movingaway from the end customers to the suppliers in a supply chain. The earliest study can be traced back to the work by Forrester (1958), who observes that a small change in retail sales can cause greater variations at upstream suppliers. The most influential studies are conducted by Lee et al (1997 a, b), which have been recognized as one of the most significant contributions in the area of supply chain management and have brought widespread academic attention. Theypropose four causes of the bullwhip effect that lead to distorted information in the order-replenishment transactions and misguide upstream members in their inventory and production decisions. Their analysis also suggests the counteractionsto alleviate the detrimental impact of the bullwhip effect.

Since then, the bullwhip effect has been observed in various industries,and evidence has suggested tremendous inefficiencies, such asunnecessary inventory, poor product forecasts, insufficient or excessive capacities, misguided planning, poor customer service due to unavailable products or long backlogs, and a low utilization of the distribution channel.Geary et al. (2006) observe that the bullwhip amplification could be as high as 20:1 from end-to-end in some supply chains. Consequently, supply chain costs could be exponentially increased.

In order to reduce its impact, a number of researchers have studied the causes of the bullwhip effect and its countermeasures.For example, Giard and Sali (2013) summarize nine causes of the bullwhip effect: reliability of forecasts, supply chain structure, demand variability, pricing policy, storage risk, lost-sizing policy, lead time variability, control model, and human factors.Wang and Disney (2016) investigate the impact of five elements on demand amplification: demand, delay, forecasting policy, ordering policy, and information sharing mechanism.

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Geary et al. (2006) propose five routes to increase the knowledge of the bullwhip effect and summarize ten causes in the literature. Among the numerous studies, we focus on four of the most prevalent causes proposed by Lee et al. (1997 a, b), that is, demand forecast, price fluctuation, anticipation of shortages, andorder batching. They are summarized as below.

- Demand forecasting: a firm only focuses on its immediate downstream partners to forecast the future demand. Forecasting errors create more variation of order quantity.
- Price fluctuation: a firmmay over-order to take advantage of the lower price, and under-order to reduce its operational cost when the price is high. As a result, its purchasing pattern is not consistent with the market demand pattern.
- Anticipation of shortages: considering the possible supply shortage, a firm may purchase the larger-than-normal quantity to secure what the market actually needed. Thus, the variation of order quantity is wider than the variation of market demand.
- Order batching: a firm accumulates the customer demands, rather than immediate issuesan order to its downstream suppliers.Time phased aggregation of orders cannot reflect the real market needs and generates more variability.

Since the bullwhip effect results in more variation, wastes and increased costs, it is closely related with the philosophy of lean production. Time issue is one of the key performance measures to various management concepts including supply chain management and lean philosophy. Especially, in this research, we mainly focus on the order cycle time, which is defined as the time period between placing two orders. The benefits of order cycle time reduction has been well realized in the lean philosophy. The shorter order cycle time can force a firm to reduce its lot size so that materials pass through the system faster, which is an important lean manufacturing strategy. It can reduce the average level of inventory, eliminate wastes by better controlling quality, smooth production by achieving a uniform workload on the system, enable Kanban and encourage continuous improvement. Overall, it will reduce variability in the system. The same logic could be borrowed to mitigate the bullwhip effect in the field of supply chain management.

The main thrust of this manuscript is to investigate the influence of order cycle time reduction on the bullwhip effect by controlling its four major causes. Specifically, four scenarios are developed to show how the order cycle time reduction could counterattack the four bullwhip effect causes at the same time. The remainder of this paper is organized as follows. In Section 2, a survey of the existing literature is carried out to familiarize ourselves with the state-of-the art development in the bullwhip effect and related areas. Then four numerical examples are conducted to investigate the relationship between the order cycle time and the bullwhip effect in Section 3. Finally, we discuss the significance of the paper and point out a few future research directions in Section 4.

2. Literature review

Since the 1990s, a large body of literature has documented the roles of information sharing and supply chain coordination to reduce the bullwhip effect (Moyaux et al., 2007; Fiala, 2005; Paik and Bagchi, 2007; Sahin and Robinson, 2002; Kok et al., 2005). More recently, many researchers attempt various approaches to identify causes, measures and remedies of the bullwhip effect (Wang and Disney, 2016). El-Tannir (2014) estimates the variance ratio of the aggregated retailer orders to the market demand. His results show that if the market demand is low,the optimal inventory review period can be derived; however, if the market demand is high, a continuous review inventory policy is better than a periodic review inventory policy. Li et al. (2014) study the bullwhip behavior when the Damped Trend forecasting method is applied with the order-up-to replenishment policy, and identify the sufficient conditions under which the bullwhip effect will be generated as well as the necessary conditions under which the bullwhip effect may be avoided. Dominguez et al. (2015) analyze the impact of the supply chain structure on the bullwhip effect. Their results show that facing a stable demand, the number of echelons is the dominant factor influencing the bullwhip effect; however, under a sudden shock in market demand, increasing the number of nodes and the divergence of the supply chain will increase the bullwhip effect. Regarding the order cycle time, much of the existing literature focuses on the inventory management and the size of production batch. Chung et al. (2015) study an integrated inventory model with a price-sensitive demand rate, and develop an algorithm to determine the optimal order cycle time and pricing decisions in order to maximize the total profit per unit time.

Chung and Huang (2006) develop a production/inventory model with imperfect quality and a permissible credit period. Their objective is to maximize the total annual profit maximization by determining the optimal cycle time and the optimal order quantity. Kim et al. (2003) suggest that a short cycle time operation at warehouse can improve the responsiveness and flexibility, however it requires planning and execution procedures to be more dynamic, real-time and intelligent. In order to realize a short cycle time without loss of productivity, they develop a new replenishment process by focusing on the minimization of setup time. Buffa and Munn (1989) develop a recursive algorithm to determine the order cycle time in order to minimize total logistics cost.Lin et al. (2002) examine the effects of information sharing on supply chain performance in electronic commerce and their results show that more detailed information sharing can reduce the order cycle time.

However, a comprehensive review of the current literature reveals limited studies about the relationship between the bullwhip effectand order cycle time, and most of discussions are about the indirect impacts of order cycle time on the bullwhip effect through other parameters, such as the lot size. Thus, this manuscript tries to contribute to the existing literature by investigating the direct impacts via controlling the causes of the bullwhip effect.

3. Impact of order cycle time on the bullwhip effect

This section describes how the order cycle time reduction affects the bullwhip effect by controlling its four causes: demand signal processing, price variations, rationing game, and order batching separately. Consistent with the existing literature (Lee et al., 1997b), a multi-period inventory system with a periodic review policy is used in a supply chain where orders are placed every fixed period (i.e., order cycle time) $T \geq 1$. In each order cycle, a replenishment is initiated to raise the inventory to the order-up-to level, *S*. In what follows, we develop a set of problem instances to examine the bullwhip effect as a function of *T*.

Let D_i be the market demand for period *i* and O_i be the order quantity for period *i*, $i \in \{1, 2, \ldots\}$. It is assumed that the lead time (i.e., the period between placing and receiving an order), *L*, is fixed and shorter than the order cycle time, i.e., $L \leq T$. It indicates that the order would be received before the next order is submitted. We also assume that only one product is involved and there are no quantity discounts in this analysis.

3.1 Demand signal processing

Now let us consider a retailer-manufacturer relationship. The timing of events can be described as follows: at the beginning of period *t*, the manufacturer estimates the would-be market demands from his retailers during the order cycle time and places an order to his suppliers with a quantity O_i; later, the replenishment order will be received at period *t* + *L*; then the available inventory will be used to meet the random market demands, D_i, till the end of order cycle at period *t* + *T*.

As suggested by Kahn (1987), Lee et al. (1997b), and Chen et al. (2000), a serially correlated demand model has been widely used in the bullwhip effect literature. Let ρ be a correlation coefficient between D_i and D_{i-1} satisfying $-1 < \rho < 1$,then the demand, D_i, can be described in an AR(1) model:

$$D_i = d + \rho D_{i-1} + e_i \qquad (1)$$

where*d* is a nonnegative constant and the error term e_i is called the"white noise" which is independently and identically normally distributed with mean 0 and variance σ^2. According to (1), the mean of demandcan be expressed as

$$E(D) = \frac{d}{1-\rho} \qquad (2)$$

Lee et al. (1997b) develop a closed-form formula to calculate the optimal order quantity, O_i, $i \in \{1, 2, \ldots, n\}$, to adjust the order-up-to inventory level based on the demand signals, that is,

$$O_i = \frac{\rho\left(1-\rho^{L+1}\right)}{1-\rho}\left(D_{i-1} - D_{i-2}\right) + D_{i-1} \quad (3)$$

To facilitate subsequent discussions, we develop a time series of market demands based on (1). Let ϱ = 0.7, d = 100, and σ = 10.EXCEL is employed to generate a set of random variables subject to the Normal distribution $N\left(0, 10^2\right)$, to simulate the random white noise e_i, $i \in \{1, 2, \ldots, n\}$. Without loss of generality, in light of (2), the initial point, D_0, can be set as the average demand, i.e., $D_0 = E(D) = \frac{d}{1-\rho} = \frac{100}{1-0.7} = 334$. According to (1), a series of correlated demand is shown in Table 1.

Table 1 Demand for periods 1-20

i	D_i	i	D_i	i	D_i	i	D_i
1	332	6	330	11	298	16	337
2	355	7	330	12	306	17	326
3	357	8	333	13	324	18	325
4	349	9	315	14	333	19	334
5	334	10	303	15	333	20	325

The manufacturer's order quantities for various order cycle times are summarized in Table 2. Let the order cycle time be $T \in \{1, 2\}$ and the lead time be L = 0.5 so that the order will be received before the next order is submitted.Taking T = 1 as an example where the manufacturerreplenishes his inventory every period, in light of (3), the order quantity for period 3 is $O_3 = \frac{\rho\left(1-\rho^{L+1}\right)}{1-\rho}\left(D_2 - D_1\right) + D_2 = \frac{0.7\left(1-0.7^{0.5+1}\right)}{1-0.7}\left(355-332\right) + 355 = 378$. Thus, compared to the actual demand for period 3, the absolute percentage error can be calculated by $\frac{\left|D_3 - O_3\right|}{D_3} = \frac{\left|357-378\right|}{357} = 5.88\%$. Similarly, if the manufacturer reviews his inventory every two periods (i.e., T = 2), the cumulative demands for the first and second order cycle are $D_1 + D_2 = 332 + 355 = 687$ and $D_3 + D_4 = 357 + 349 = 706$ respectively.Then, according to (3), the corresponding replenishment order quantity for the third order cycle (i.e., periods 5 and 6) can be calculated by $\frac{0.7\left(1-0.7^{0.5+1}\right)}{1-0.7}\left(706-687\right) + 706 = 725$. Since the actual demand for the third order cycle is $D_5 + D_6 = 334 + 330 = 664$, the absolute percentage error is $\frac{\left|664-725\right|}{664} = 9.19\%$.

Table 2 Demand and order quantity for various order cycle time

	$T=1$			$T=2$		
i	D_i	O_i	$\frac{\lvert D_i - O_i \rvert}{D_i}$	D_i	O_i	$\frac{\lvert D_i - O_i \rvert}{D_i}$
1	332					
2	355			687		
3	357	378	5.88%			
4	349	359	2.87%	706		
5	334	342	2.40%			
6	330	320	3.03%	664	725	9.19%
7	330	327	0.91%			
8	333	330	0.90%	663	624	5.88%
9	315	336	6.67%			
10	303	298	1.65%	618	663	7.28%
11	298	292	2.01%			
12	306	294	3.92%	604	575	4.80%
13	324	314	3.09%			
14	333	342	2.70%	657	591	10.05%
15	333	342	2.70%			
16	337	333	1.19%	670	709	5.82%
17	326	341	4.60%			
18	325	316	2.77%	651	683	4.92%
19	334	325	2.69%			
20	325	343	5.54%	659	633	3.95%
Mean			3.08%			6.48%
S.D.	15.32	22.04		29.66	54.03	

As shown in Table 2, when T = 1, the standard deviations of order quantity and demand are 22.04 and 15.32 respectively, which indicates $\text{Var}(O_i) > \text{Var}(D_i)$. It suggests the occurrence of bullwhip effect where the variance of order quantity increases as moving away from the retailer to the manufacturer in a supply chain. The similar observation can be obtained for T = 2where $\text{Var}(O_i) = 54.03^2 > \text{Var}(D_i) = 29.66^2$. By comparing the cases with T = 2 and T = 1, it can be shown that the degree of variance amplification has been reduced from $\frac{54.03^2 - 29.66^2}{29.66^2} = 231.84\%$ to $\frac{22.04^2 - 15.32^2}{15.32^2} = 106.97\%$. This makes logical sense since when the manufacturer launches the shorter order cycle time operation, the information can be revised more frequently to match the actual market demands, which would reduce information variation on each supply chain member. As a result, itimproves the forecasting accuracy and mitigates the bullwhip effect. In addition, when the order cycle time is set as 2 periods, it is reported in Table 2 that the mean absolute percentage error (MAPE) is $\frac{1}{n}\sum_{i=1}^{n}\frac{\lvert D_i - O_i \rvert}{D_i} = 6.48\%$; however, as the order cycle time is reduced to 1 period, MAPE is decreased to $\frac{1}{n}\sum_{i=1}^{n}\frac{\lvert D_i - O_i \rvert}{D_i} = 3.08\%$.

Since MAPE measures the accuracy of supply balance to meet demands, it indicates that compared to the actual demands, the supply error, on average, can be improved by 6.48% – 3.08% = 3.4% when the order cycle time is reduced by 50%.

3.2 Price fluctuation

In order to keep consistency with the previous example, we still consider a two-echelon supply chain with a manufacturer and a retailer. As indicated by Lee et al. (1997a, b), one of the major causes of the bullwhip effect is that supply chain members intend topurchase larger-than-normal amounts to hedge against the increase in price.As a result, the order quantity does not reflect the immediate market needs.

Assume that the price at period *i*, p_i, is a random variable which takes the low value with probability *q* and the high value with probability 1 – *q*. When the price is low, the manufactureris willing to hold more inventory to improve his service level (i.e., the probability of not stocking out)when facing uncertain demands from his retailers. Ina periodic review model where the order interval is fixed, it indicates that the target inventory position should be increased, which is measured by the order-up-to inventory level,*S*. However, when the price is high, the manufacturer is motivated to hold less inventory to keep operation costs within reasonable bounds. As a result, the inventory policy should be adjusted to lower the service level and the order-up-to level. Obviously, the decision of the order quantity is determined by the fluctuation of purchasing price and the uncertainty of market demand.

Let z_i be the number of standard deviation of standard Normal distribution for a given service level at period *i*, then the order-up-to inventory level can be expressed as

$$S_i = \mu_d(T+L) + z_i\sigma_d\sqrt{T+L} \tag{4}$$

where μ_d and σ_d are the mean and standard deviation of market demand respectively. So, the order quantity at period *i*, O_i ,can be calculated by

$$O_i = \max(S_i - (S_{i-1} - D_i), 0) \tag{5}$$

In this analysis, it is assumed that the service level will be maintained at 99.99% if the price is low, then the corresponding *z* value for the standard Normal distribution is 3.71; however, the service level will be reduced to 80% if the price is high, and its corresponding *z* value is changed to 0.84.Considering the demands shown in Table 1, we have $\mu_d = 328.95$ and $\sigma_d = 15.32$ .Same as previous definitions, let the order cycle time be $T \in \{1, 2\}$ and the lead time be L = 0.5. In light of (4), the order-up-to inventory level (S_i) for the various combinations of p_i and T with L = 0.5 is summarized in Table 3. For example, when p_i is low and T = 1, the order-up-to inventory level can be calculated by $S_i = \mu_d(T+L) + z_i\sigma_d\sqrt{T+L} = 328.95 \times (1+0.5) + 3.71 \times 15.32 \times \sqrt{1+0.5} = 564$ .However, when p_i is high and T = 2, we have $S_i = \mu_d(T+L) + z_i\sigma_d\sqrt{T+L} = 328.95 \times (2+0.5) + 0.84 \times 15.32 \times \sqrt{2+0.5} = 843$.

Table 3 Order-up-to inventory level for various order cycle time and Price

S_i		T	
		$T=1$	$T=2$
p_i	low	564	913
	high	510	843

The manufacturer's order quantities for various order cycle times and prices are summarized in Table 4. Let *q* = 0.5, which indicates that low-high pricing occurs with a 50/50 chance. EXCEL is employed to generate a set of random variables subject to the Bernoulli distributionB(1, 0.5), to simulate the random price p_i , $i \in \{1, 2, \ldots, 20\}$. Without loss of generality, it is assumed that p_0 is low at the initial period 0. Taking T = 1 as an example, in light of (5), the order quantities for period 1 and 2 are $O_1 = \max(S_1 - (S_0 - D_1), 0) = \max(564 - (564 - 332), 0) = 332$ and $O_2 = \max(S_2 - (S_1 - D_2), 0) = \max(510 - (564 - 355), 0) = 301$.

Thus, compared to the actual demand for period 1 and 2, the absolute percentage errors can be calculated as $\frac{|D_1 - O_1|}{D_1} = \frac{|332-332|}{332} = 0$ and $\frac{|D_2 - O_2|}{D_2} = \frac{|355-301|}{355} = 15.21\%$. Similarly, if T = 2, according to (5), the corresponding replenishment order quantity for the first order cycle (i.e., periods 1 and 2) can be calculated by $\max(843-(913-687), 0) = 617$, and the absolute percentage error is $\frac{|687-617|}{687} = 10.19\%$.

Table 4Demand and order quantity for various order cycle time and Price

i	p_i	$T=1$				$T=2$			
		D_i	S_i	O_i	$\frac{\vert D_i - O_i\vert}{D_i}$	D_i	S_i	O_i	$\frac{\vert D_i - O_i\vert}{D_i}$
1	low	332	564	332	0				
2	high	355	510	301	15.21%	687	843	617	10.19%
3	low	357	564	411	15.13%				
4	low	349	564	349	0	706	913	776	9.92%
5	high	334	510	280	16.17%				
6	high	330	510	330	0	664	843	594	10.54%
7	high	330	510	330	0				
8	low	333	564	387	16.22%	663	913	733	10.56%
9	low	315	564	315	0				
10	low	303	564	303	0	618	913	618	0
11	low	298	564	298	0				
12	low	306	564	306	0	604	913	604	0
13	high	324	510	270	16.67%				
14	high	333	510	333	0	657	843	587	10.65%
15	high	333	510	333	0				
16	low	337	564	391	16.02%	670	913	740	10.45%
17	low	326	564	326	0				
18	high	325	510	271	16.62%	651	843	581	10.75%
19	low	334	564	388	16.17%				
20	low	325	564	325	0	659	913	729	10.62%
Mean					6.41%				8.37%
S.D.		15.32		32.92		29.66		76.43	

As shown in Table 4, the bullwhip effect can be observed since $\mathrm{Var}(O_i) > \mathrm{Var}(D_i)$ for both$T$ = 1 and$T$ = 2. By comparing the cases with T = 2 and T = 1, it can be seen that the degree of variance amplification has been reduced from $\frac{76.43^2 - 29.66^2}{29.66^2} = 564.03\%$ to $\frac{32.92^2 - 15.32^2}{15.32^2} = 361.74\%$. It suggests that the order cycle time reduction would mitigate the bullwhip effect. One of the possible explanations is that, by applying the shorter order cycle time, each supply chain member can quickly respond to the unstable market price and store less inventory for the short period, which will reduce the changes in the order quantity.

In addition, as reported in Table 4,as the order cycle time is reduced from 2 periods to 1 period, MAPE is also decreased from 8.37% to 6.41%. It indicates that the supply error isimproved by 8.37% – 6.41% = 1.96%.

3.3Rationing and shortage game

Now let us consider a shortage situation where demand exceeds supply due to unexpected increase in market needs or limitation in production capacity.

When a supply chain faces a shortage, the downstream partner only has ability to deliver a proportion of orders placed by its upstream partners. In order to compensate for business loss, the upstream partners often buy in quantities that exceed immediate requirements to secure more units. This causes the bullwhip effect in that the variance of order quantity increases as demands move up in a supply chain.

Assume that the unstable market demand, D_i, follows a Normal distribution, $N(\mu_d, \sigma_d^2)$, and σ_d^2 is a relatively large value to μ_d to represent the shortage situation caused by the unexpected big changes in demand. In this analysis, a Newsvendor model is used to balance the costs of inventory over-stock and under-stock.If there is no risk of supply shortage (i.e., the supply of the product is unlimited), the optimal order-up-to inventory level at period *i*, S_i, is

$$S_i = \mu_d + z\sigma_d \tag{6}$$

wherezis the *z*-score for the standard Normal distribution that yields the service level, $\frac{c_u}{c_u + c_o}$. Here c_u and c_o represent the underage cost and overage cost per unit in the Newsvendor model. However, if the demand is higher than the available supply, the manufacturer may only get a percentage of his orders. In such a case, the manufacturer will increase his order-up-to inventory level and place an order with larger-than-normal amounts to handle the short of supply. Let a be the percentage of orders placed by the supplier which follows a uniform distribution, $U(\underline{v}, \bar{v})$, $0 \le \underline{v} < \bar{v} \le 1$, and we have $E(\alpha) = \frac{\underline{v} + \bar{v}}{2}$. Then facing the supply shortage, the order-up-to inventory level at period *i*, S_i, is changed to

$$S_i = \frac{\mu_d + z\sigma_d}{E(\alpha)} = \frac{\mu_d + z\sigma_d}{\frac{\underline{v} + \bar{v}}{2}} = \frac{2(\mu_d + z\sigma_d)}{\underline{v} + \bar{v}} \tag{7}$$

Without loss of generality, if the demand at period *i*, D_i, is higher than the normal optimal order-up-to inventory level, S_i, in (6), the manufacturer will buy the larger-than-normal amounts to reduce the probability of supply shortage. In sum, according to (6) and (7), the order-up-to inventory level at period *i*, S_i, can be written as

$$S_i = \begin{cases} \mu_d + z\sigma_d & D_i \le \mu_d + z\sigma_d \\ \frac{2(\mu_d + z\sigma_d)}{\underline{v} + \bar{v}} & D_i > \mu_d + z\sigma_d \end{cases} \tag{8}$$

So, the order quantity at period *i*, O_i ,can be calculated by

$$O_i = \max(S_i - (S_{i-1} - D_i), 0) \tag{9}$$

In this analysis,let $\mu_d = 400$ and $\sigma_d = 100$, then EXCEL is employed to generate a set of random variables subject to the Normal distribution $N(400, 100^2)$, to simulate the demand D_i, $i \in \{1, 2, \ldots, 20\}$.Since the purpose of this analysis is to avoid the business loss due to stockout, it is reasonable to letthe underage cost be twice of the overage cost, then the service level is $\frac{c_u}{c_u + c_o} = \frac{1}{1 + \frac{c_o}{c_u}} = 0.67$ and the corresponding *z*-value is 0.44. In addition, let $\underline{v} = 0.5$ and $\bar{v} = 1$ so that a follows the Uniform distribution U(0.5, 1).

As before, let the order cycle time be $T \in \{1, 2\}$. When *T* = 1, in light of (8), the order-up-to inventory level at period *i*, S_i, is

$$S_i = \begin{cases} \mu_d + z\sigma_d & D_i \le \mu_d + z\sigma_d \\ \dfrac{2(\mu_d + z\sigma_d)}{\underline{v} + \bar{v}} & D_i > \mu_d + z\sigma_d \end{cases}$$

$$= \begin{cases} 400 + 0.44 \times 100 & D_i \le 400 + 0.44 \times 100 \\ \dfrac{2 \times (400 + 0.44 \times 100)}{0.5 + 1} & D_i > 400 + 0.44 \times 100 \end{cases}$$

$$= \begin{cases} 444 & D_i \le 444 \\ 592 & D_i > 444 \end{cases} \qquad (10)$$

When T = 2, since the demand at each period is independent, we have $\mu_d = 400 \times 2 = 800$ and $\sigma_d = 100 + 100 = 200$. Then, according to (8), S_i is increased to

$$S_i = \begin{cases} 888 & D_i \le 888 \\ 1184 & D_i > 888 \end{cases} \qquad (11)$$

The manufacturer's order quantities for various order cycle times are summarized in Table 5. It is assumed that the demand is low without the shortage risk at the initial period 0. Taking T = 1 as an example, in light of (10), the order quantities for period 1 and 2 are $O_1 = \max(S_1 - (S_0 - D_1), 0) = \max(592 - (444 - 491), 0) = 639$ and $O_2 = \max(S_2 - (S_1 - D_2), 0) = \max(592 - (592 - 550), 0) = 550$. Thus, compared to the actual demand for period 1 and 2, the absolute percentage errors can be calculated as $\frac{|D_1 - O_1|}{D_1} = \frac{|491 - 639|}{491} = 30.14\%$ and $\frac{|D_2 - O_2|}{D_2} = \frac{|550 - 550|}{550} = 0$. Similarly, if T = 2, according to (11), the corresponding replenishment order quantity for the first order cycle (i.e., periods 1 and 2) can be calculated by $\max(1184 - (888 - 1041), 0) = 1337$, and the absolute percentage error is $\frac{|1041 - 1337|}{1041} = 28.43\%$.

Table 5 Demand, order-up-to level and order quantity for various order cycle time

	$T=1$				$T=2$			
i	D_i	S_i	O_i	$\frac{\lvert D_i-O_i\rvert}{D_i}$	D_i	S_i	O_i	$\frac{\lvert D_i-O_i\rvert}{D_i}$
1	491	592	639	30.14%				
2	550	592	550	0	1041	1184	1337	28.43%
3	379	444	231	39.05%				
4	297	444	297	0	676	888	380	43.79%
5	371	444	371	0				
6	328	444	328	0	699	888	699	0
7	534	592	682	27.72%				
8	450	592	450	0	984	1184	1280	30.08%
9	580	592	580	0				
10	384	444	236	38.54%	964	1184	964	0
11	423	444	423	0				
12	361	444	361	0	784	888	488	37.76%
13	526	592	674	28.14%				
14	341	444	193	43.40%	867	888	867	0
15	499	592	647	29.66%				
16	527	592	527	0	1026	1184	1322	28.85%
17	543	592	543	0				
18	448	592	448	0	991	1184	991	0
19	515	592	515	0				
20	416	444	268	35.58%	931	1184	931	0
Mean				13.61%				16.89%
S.D.	85.28		157.33		133.81		333.62	

As shown in Table 5, the bullwhip effect can be observed since $\text{Var}(O_i) > \text{Var}(D_i)$ for both T = 1 and T = 2. By comparing the cases with T = 2 and T = 1, it can be seen that the degree of variance amplification has been reduced from $\frac{333.62^2 - 133.81^2}{133.81^2} = 521.66\%$ to $\frac{157.33^2 - 85.28^2}{85.28^2} = 240.36\%$. MAPE is also decreased from 16.89% to 13.61%. It indicates that the supply error isimproved by 16.89% – 13.61% = 3.28%. It suggests that the order cycle time reduction would mitigate the bullwhip effect. The implication is that, by using the shorter order cycle time, each supply chain member can reduce the probability and amount of supply shortage, which will reduce the uncertainty in the order quantity.

3.4 Order batching

Order batching refers to grouping different demands in only one batch in order to take advantage of transportation costs and sales incentives. Clearly, the order cycle time will be longer if demands are accumulated before issuing an order to suppliers. In practice, reducing the order cycle time is equivalent to decreasing the batch size in a multi-period inventory system with a periodic review policy. The effect of small batch size on the bullwhip effect has been well studied in the existing literature. For example, Lee et al. (1997b) discuss three different forms of order batching: random ordering, correlated ordering and balanced ordering, and their results show that in all three cases, the variance of orders is amplified in a supply chain. So, it indicates that the order cycle time reduction forces each supply chain member adapt the smaller batch size, which will mitigate the bullwhip effect.

As illustrated in previous examples, no matter which forecasting approach or inventory model is used, it seems that larger orders result in more variance. For example, as shown in Table 2, we have $Var(O_i) = 54.03^2$ for T = 2 and $Var(O_i) = 22.04^2$ for T = 1, it suggests that the variance of order quantity is reduced by $\frac{54.03^2 - 22.04^2}{22.04^2} = 500.96\%$ as the order cycle time is decreased from 2 periods to 1 period. The similar observations can also be obtained in Tables 4 and 5 where the variability of order is reduced by $\frac{76.43^2 - 32.92^2}{32.92^2} = 439.02\%$ and $\frac{333.62^2 - 157.33^2}{157.33^2} = 349.66\%$ respectively as the order cycle time is changed from T = 2 to T = 1.

4. Discussions and Conclusions

This research is concerned with the impacts of order cycle time on the bullwhip effect by considering its four major causes proposed by Lee et al. (1997a, b), i.e., demand forecast, price fluctuation, anticipation of shortages, andorder batching.Fournumerical examples are developed to show how the order cycle time reduction could counterattack these four causes at the same time.Considering a two-echelon supply chain, a multi-period inventory system with a periodic review policy is used where orders are placed every fixed period. In each order cycle, a replenishment is initiated to raise the inventory to the order-up-to level, and the variance ratio of the manufacturer order to the market demandis calculated. Our results show that by comparing the various order cycle times, the degree of variance amplification has been reduced for the shorter inventory review cycle. In addition, in order to evaluate the accuracy of supply balance to actual demand, MAPE is calculated and indicates that the supply error, on average, can be improved when the order cycle time is reduced. In conclusion, our analysis suggests that the order cycle time reduction would mitigate the bullwhip effect.

The present work should be viewed only as a first step towards a better understanding of the impacts of order cycle time on the bullwhip effect. Clearly, more research is needed. Some limitations and future research directions should be mentioned here. Firstly, from the methodology perspective, the mathematical modeling or empirical survey should be conducted later to generalize the results to various situations.

Secondly, from a practical perspective, the further analysis is needed to consider other causes of the bullwhip effect, especially the human behavior causes. For example, Nienhaus et al. (2006) suggest that human capital is one of the important factors to cause the bullwhip effect. In addition,Bhattacharya and Bandyopadhyay(2011) survey the existing literature and summarize 19 important bullwhip effect causes. Three of them are behavior causes.

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