Australian Journal of Basic and Applied Sciences, 8(14) Special 2014, Pages: 70-77

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

Understanding the Impact of Replenishment Lead Times on the Bullwhip Effect in Dual-Sourcing Supply Chains

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ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form
8 July 2014
Accepted 10 August May 2014
Available online 30 September 2014

Keywords:
Bullwhip Effect, Dual sourcing model, Supply Chain, Replenishment lead time, Order-up-to level policy

ABSTRACT

At present, research studies on the increasing demand amplification, or the bullwhip effect (BWEF), under a dual-sourcing supply chain network are limited. In addition, no existing research clearlystates whether and howorder lead times influence the bullwhip effect under the dual-sourcing supply chain environment.This research thus investigates these questions through an analytical approach by which a retailer's orders are divided between two distributors. Both cases of equal and unequal lead times at the distributors-retailer links are examined, and the incoming demand modelis assumed the first-order autoregressive process.The findings indicate that an increase in lead times is not necessarilyaccompanied byan increase in thebullwhip effect.

To Cite This Article: Kittiwat Sirikasemsuk, Understanding the Impact of Replenishment Lead Times on the Bullwhip Effect in Dual-Sourcing Supply Chains. ***Aust. J. Basic & Appl. Sci.**, 8(14): 70-77, 2014*

INTRODUCTION

It was first observed by Forrester (1958) that the variation in order quantities at the upstream nodes of a supply chain was noticeably larger than that in customer demands at the downstream nodes, a phenomenonwhich islater called the bullwhip effect, abbreviated BWEF in this paper. Lee *et al*. (1997) informed the incidence of the BWEFin real business situations, e.g. in Hewlett-Packard and Procter & Gamble.Theyidentifiedthe negative consequences (e.g. undesirable stock-outs, over-production) and causes (e.g. demand forecast, shortage, and price variation) of the BWEF. In addition, reviews of literature on the causes of BWEF and its remedies were carried out by Bhattacharya and Bandyopadhyay (2011) andGeary *et al*. (2006). The BWEF is now one of major performance indicators of supply chain management.

Prior research studiesexamined the behavior of BWEF usingdifferent forecasting techniques in an attempt to identify the parameters associated with the demand forecast.Chen *et al*. (2000a) established the gauge of BWEFusing the moving average (MOA) forecasting method under the first-order autoregressive, AR(1), model. It was found that the bullwhip ratio decreases with increase in the number of periods of past actual demand.Besides, Chen *et al*. (2000b) investigated the influence of the exponential (EXPON) smoothing method on the BWEF under the correlated demand process (i.e. the AR(1) model) and the linear-trend demand process. It was proved that the variation of order quantity using theMOA forecasting method is less than that using theEXPON smoothing forecasting method. In addition, Wang (2008) analyzed the variation using the double MOA and double EXPON smoothing forecasts.

Wright and Yuan (2008) simulated the effects of several forecasting methods (e.g. thesimple EXPONsmoothing, double EXPON smoothing and simple MOAforecasting plans) and the effects of order policies on the BWEF based on Sterman's procedure. Bayraktar *et al*. (2008),who examined the electronic SCM (E-SCM) with a simpleonline supply chain in which demand information was shared between the supply chain members,utilized the Holt-Winters method, also known as the triple EXPON smoothing method, through simulation at an online retailer. Both studiesreported that the parameters of the forecasting methodsconsiderably influence the BWEF. They also suggested that their small parameters' values of the EXPON-based forecasting techniques led to the low magnitude of the BWEF.

In addition to the simple forecasting methods, the minimum mean square error (MMSE) forecasting method, a more sophisticated forecasting method, has been applied in several research studies for the Box–Jenkins time series in which a family of the autoregressive integrated moving average (ARIMA) processes is proposed.For example, Luong (2007) and Hosoda and Disney (2005)established the measure of the BWEF for

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the AR(1) demand process. Duc *et al*. (2008a) and Gaalman and Disney (2006)examined the mixed first-order autoregressive-moving average demand process. Luong and Phien (2007) studied the BWEF for the second-order and general autoregressive models. It should be noted that the MMSE method performs better than the MOA and EXPON methods for stationary demand processes.

Order lead time isanother factor contributing to the existence of BWEF. Chen *et al*. (2000a, b), Wang *et al*. (2008) and Bayraktar *et al*. (2008) reported that the variance amplification under longer lead times is more pronounced than that under shorter lead times. On the effect of stochastic lead time, Duc *et al*. (2008b) found that the BWEF increases with increase in the variance of lead time. Chatfield *et al*. (2004), who utilized the MOA method and simulation, noted that the higher the coefficient of leadtime variation, the greater the BWEF, given that the customer demand followed a normal distribution. Luong and Phien (2007) and Duc *et al*. (2008a) interestingly noted that an increase in lead times is not necessarily accompanied by an increase in the BWEF.

The supply chain structure of all aforementioned studies is of a single sourcing environment, i.e. retailer(s) source the product from onesupplier. On the other hand, research studiesbySirikasemsuk and Luong (2014) and Sirikasemsuk (2014) seem to be the earliest papersthat recognize the BWEF under the dual sourcing model with one retailer, two distributors and one supplier.Bothaforementioned studies used the MMSE forecasting technique for the AR(1) demand process. In the former, the focus was on a two-sourcing supply chain with unequal lead times at the distributors-retailer links, while the latter concentrated on a model with identical lead times atthe distributors-retailer links. However, both papers do not include the in-depth details of the impact of lead times on the BWEF. Hence, the aim of this current paper is to demonstrate how lead times influence the BWEFfor the dual-sourcing supply chain. In addition, this research is an extension of the research bySirikasemsuk (2014) and Sirikasemsuk and Luong (2014).

The notations used in this research and their respective meanings are provided below.

k index of distributors (k =1 or 2)
M index of models (M = A or B)
δ the constant of the autoregressive model
D_t customer demand of the retailer in time period t
ϕ the first-order autocorrelation coefficient and $|\phi| \le 1$ for stationary process
ε_t forecast error term for period t at which ε_t is independent and identically distributed and ε_t ~ normal(0, σ^2)
$\hat{D}_{t+j}$ demand forecast by the retailer in time period $t+j$
$q_{k,t}^M$ order quantity issued by the retailer to distributor k in time period t of Model-M
Q_t^M total order quantity placed by the retailer of Model-M at the beginning of period t
S_t^M order-up-to level of the retailer of Model-M at the beginning of period t
$r_{k,t}^M$ order quantity issued by distributor k to the supplier in time period t of Model-M
R_t^M total order quantity received by the supplier of Model-M at the beginning of period t
α proportion of order quantity issued by the retailer to distributor 1 for Model-A where $\alpha = [0,1]$
$1-\alpha$ proportion of order quantity issued by the retailer to distributor 2 for Model-A
L_k order lead time between distributor k and the retailer
l_k order lead time between the supplier and distributor k

Three-echelon dual-sourcing supply chains:

The models in this research are based on the single-item three-echelon supply chain configuration consisting of one retailer, two distributors and one supplier (see Figures 1 and 2). The AR(1)stationary demand process is assumed at the retailer to generate random demand of each period and can be defined by Equation (1).

$$D_t = \delta + \phi D_{t-1} + \varepsilon_t \tag{1}$$

The retailer and the two distributors make a forecast of their respective demands using the MMSE forecasting plan. Every member in the supply chainapplied the order-up-to level inventory policies so as todetermine the order quantities at the beginning of period *t*prior to placing the orderwith thepreceding member(s). For example, total demand forecast during the retailer's lead time with the MMSE forecasting method can be derived by Equation (2);and at the beginning of period *t*, total order quantity by the retailer can be determined by Equation (3).

$$\hat{D}_{t+j} = E[D_{t+j} \mid D_{t-1}, D_{t-2}, \ldots, D_1] \tag{2}$$

$$Q_t^M = \begin{pmatrix}\text{order - up - to level}\\ \text{at the beginning of period t}\end{pmatrix} - \begin{pmatrix}\text{inventory position}\\ \text{at the beginning of period t}\end{pmatrix} = S_t^M - (S_{t-1}^M - D_{t-1}) \quad (3)$$

Note that the main goal of this inventory policy is tobalancea trade-off between costs of inventory holding and poor services (Cachon and Terwiesch, 2013).

Given the lead times between the distributors and the retailer, there are two possible models.

Model-A: a three-stage dual-sourcing supply chain under*equal lead times*atthe distributors-retailer links (see Figure 1)

Model-B: a three-stage dual-sourcing supply chain under *unequal lead times*at the distributors-retailer links (see Figure 2)

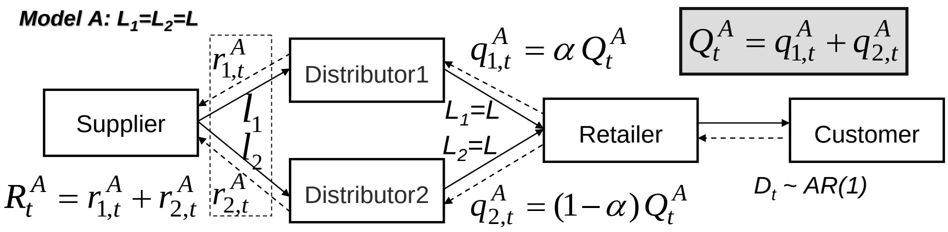

Fig. 1: The dual sourcing model with identical lead times for distributors-retailer links (Model-A) (Sirikasemsuk, 2014)

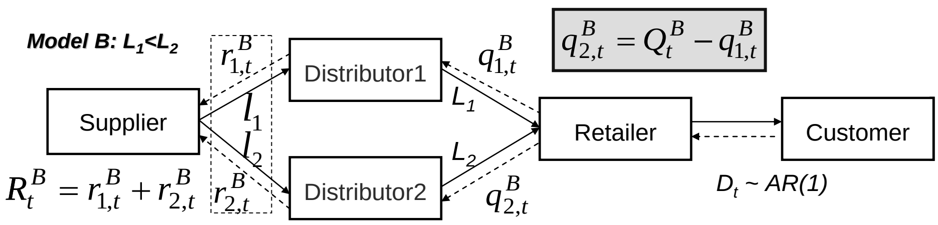

Fig. 2: The dual sourcing model with unequal lead times for distributors-retailer links (Model-B) (Sirikasemsuk and Luong, 2014)

In both models, the order lead times are assumed deterministic, not stochastic. The ordered products by distributors 1 and 2 are dispatchedby the supplier after l_1 and l_2 periods, respectively. The lead times l_1 and l_2 are not necessarily equal and could be any positive integers.

Similar to Sirikasemsuk (2014), Model-A assumes that the lead times at the distributors-retailer links are identical, i.e. $L_1 = L_2 = L$. The total order quantity, Q_t^A , isderived based on the demand forecast over the lead time L periods. Q_t^A is then split between distributors 1 and 2 by constant proportion parameters, α and $1-\alpha$, respectively; hence, we have the following relationships: $q_{1,t}^A = \alpha Q_t^A$ and $q_{2,t}^A = (1-\alpha) Q_t^A$.

Without loss of generality, in Model-B,similar to Sirikasemsuk and Luong (2014), the lead time between distributor1 and the retailer is less than that between distributor2 and the retailer, i.e. $L_1 < L_2$. In Figure 2, it is crucial to note that with the MMSE forecasting technique, the orders received by distributors 1 and 2 are not readilydivided from the total order quantity, Q_t^B with a constant parameter. According to Sirikasemsuk and Luong (2014), Q_t^B can be calculated based on the demand forecast over the longer lead time L_2 periods, and $q_{1,t}^B$ can be determined by the demand forecast over the shorter lead time L_1 periods. $q_{2,t}^B$ canthen be determined by $q_{2,t}^B = Q_t^B - q_{1,t}^B$. For greater details on this inventory policy under the dual sourcing environment in the case of $L_1 < L_2$, readers are advised to refer to the studybySirikasemsuk and Luong (2014).

In general, theextent of the BWEF is determinedthrough dividing the variance of order quantity at the upstream member by the variance of demand at the downstream member. Similarly, in this research, the BWEF measures for Model-A and Model-B are defined as Equation (4).

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$$BWEF_{Model-M} = \frac{VAR(R_t^M)}{VAR(D_t)} = \frac{VAR(r_{1,t}^M + r_{2,t}^M)}{VAR(D_t)} \quad (4)$$

Determination of bullwhip effects under dual sourcing models:

Sirikasemsuk (2014) and Sirikasemsuk and Luong (2014) derived the equations of the BWEF for Model-A (i.e. the case of $L_1 = L_2 = L$) and Model-B (i.e. the case of $L_1 < L_2$),which are expressed as

$$BWEF_{\text{Model-A}}(\alpha,\phi,l_1,l_2,L) = 1 + \frac{2\left[\phi - \phi^{L+l_2} + \alpha\phi^{L+l_2} - \alpha\phi^{L+l_1}\right]\left[1 - \phi^{L+l_2} + \alpha\phi^{L+l_2} - \alpha\phi^{L+l_1}\right]}{1-\phi}, \quad (5)$$

and

$$BWEF_{\text{Model-B}}(\phi,l_1,l_2,L_1,L_2) = 1 + \frac{2}{(1-\phi)^3}\left[\left(\phi - \phi^2 + \phi^{l_1+L_1+1} - \phi^{l_2+L_1+1} - \phi^{l_1+L_2} + \phi^{l_2+L_2+1}\right) * \left(1 - \phi + \phi^{l_1+L_1+1} - \phi^{l_2+L_1+1} - \phi^{l_1+L_2} + \phi^{l_2+L_2+1}\right)\right]. \quad (6)$$

It was proved that the BWEF does not always exist for negative autocorrelation coefficients in both supply chain models. For positive autocorrelation coefficients, the BWEF always exists in Model-A ($L_1 = L_2 = L$); however, in Model-B ($L_1 < L_2$), the BWEF does not exist, if all the following conditions are true:

1) $l_1 > l_2 + 1,$ (7)

2) $L_2 > L_1 + 1,$ (8)

3) $\left(1 - \phi + \phi^{l_1+L_1+1} - \phi^{l_2+L_1+1} - \phi^{l_1+L_2} + \phi^{l_2+L_2+1}\right) \geq 0$ *and* $\left(\phi - \phi^2 + \phi^{l_1+L_1+1} - \phi^{l_2+L_1+1} - \phi^{l_1+L_2} + \phi^{l_2+L_2+1}\right) \leq 0$ (9)

For the proof, see Sirikasemsuk and Luong (2014).

Effects of replenishment lead times:

The remainder of this paper is concerned with $0 > \phi > 1$, which could lead to the existence of BWEF. The impacts of equal and unequal lead times on the BWEF can be determined by Propositions 1 and 2, respectively.

Proposition 1 *For Model-A (* $L_1 = L_2 = L$ *) and positive autocorrelation coefficients, the BWEF under the dual sourcing environment increases with increase in either* L *,* l_1 or l_2 *. With the longer lead times, the BWEFs approach the following specific values:*

(a) $\lim_{L\to\infty} BWEF_{\text{Model-A}} = 1 + \frac{2\phi}{1-\phi}$

(b) $\lim_{l_1\to\infty} BWEF_{\text{Model-A}} = 1 + \frac{2\left[\phi - \phi^{L+l_2}(1-\alpha)\right]\left[1 - \phi^{L+l_2}(1-\alpha)\right]}{1-\phi}$

(c) $\lim_{l_2\to\infty} BWEF_{\text{Model-A}} = 1 + \frac{2\left[\phi - \alpha\phi^{L+l_1}\right]\left[1 - \alpha\phi^{L+l_1}\right]}{1-\phi}$.

Proof. Equation (5) can be rewritten as

$$BWEF_{\text{Model-A}}(\alpha,\phi,l_1,l_2,L) = 1 + \frac{2\left[\phi - \phi^L\left(\phi^{l_2} + \alpha\left(\phi^{l_1} - \phi^{l_2}\right)\right)\right]\left[1 - \phi^L\left(\phi^{l_2} + \alpha\left(\phi^{l_1} - \phi^{l_2}\right)\right)\right]}{1-\phi} \quad (10)$$

From Equation (10), it is easy to show that the expression $\left(\phi^{l_2} + \alpha\left(\phi^{l_1} - \phi^{l_2}\right)\right)$ is always positive for $0 < \phi \leq 1$ with any $l_1$and l_2. Hence, an increase in L causes the values in $\phi^L\left(\phi^{l_2} + \alpha\left(\phi^{l_1} - \phi^{l_2}\right)\right)$ to decrease andthe value of every componentin everysquare bracket to increase, thereby amplifying the BWEF.

From Equation (5), when l_1 or l_2 increases, the BWEF increases. Note that $-\phi^{L+l_2} + \alpha\phi^{L+l_2} = -\phi^{L+l_2}(1-\alpha)$ to simplify the term of the increase of l_2 .Taking the limits of function (5) as each lead time approaches infinity, Propositions 1(a) to 1(c) are proved. This completes the proof. □

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Proposition 2 *For Model-B ($L_1 < L_2$) and positive autocorrelation coefficients, the BWEF under the dual sourcing environment has the following properties.*

(a) If l_1 increases, the BWEF decreases (see Figure 3).*

(b) If l_2 increases, the BWEF increases (see Figure 3).

*(c) In case of $l_1 < l_2$, when L_1 increases, the BWEF decreases**(see Figure 4a). Nonetheless, in case of $l_1 > l_2$, when L_1 increases, the BWEF increases** (see Figure 4b).*

*(d) In case of $l_1 < l_2+1$, when L_2 increases, the BWEF increases*** (see Figure 5a). Nonetheless, in case of $l_1 > l_2+1$, when L_2 increases, the BWEF decreases*** (see Figure 5b).*

(e) For the case when $l_1 = l_2 = l'$, if the lead time L_2 or l' increases, the BWEF increases (see Figure 6).

Notes: * the case of $L_2 = L_1+1$ in which the BWEF does not depend on l_1, which is exempted from Proposition 2(a);

** the case of $l_1 = l_2$ in which the BWEF does not depend on L_1, which is exempted from Proposition 2(c);

*** the case of $l_1 = l_2+1$ in which the BWEF does not depend on L_2, which is exempted from Proposition 2(d).

- the cases when both expressions $(\phi - \phi^2 + \phi^{l_1+L_1+1} - \phi^{l_2+L_1+1} - \phi^{l_1+L_2} + \phi^{l_2+L_2+1})$ and $(1 - \phi + \phi^{l_1+L_1+1} - \phi^{l_2+L_1+1} - \phi^{l_1+L_2} + \phi^{l_2+L_2+1})$ are negative, resulting in the outcomes may not follow Propositions 2(a), 2(b), 2(c), and 2(d).

Proof. To identify the effects of lead times, the bullwhip ratio in Equation (6) can be rewritten as

$$BWEF_{\text{Model-B}}(\phi, l_1, l_2, L_1, L_2) = 1 + \frac{2}{(1-\phi)^3}\left\{\left(\phi(1-\phi) + \phi^{l_1}\left(\phi^{L_1+1} - \phi^{L_2}\right) - \phi^{l_2+1}\left(\phi^{L_1} - \phi^{L_2}\right)\right) * \left(1 - \phi + \phi^{l_1}\left(\phi^{L_1+1} - \phi^{L_2}\right) - \phi^{l_2+1}\left(\phi^{L_1} - \phi^{L_2}\right)\right)\right\} \tag{11}$$

or

$$BWEF_{\text{Model-B}}(\phi, l_1, l_2, L_1, L_2) = 1 + \frac{2}{(1-\phi)^3}\left\{\left(\phi(1-\phi) + \phi^{L_1+1}\left(\phi^{l_1} - \phi^{l_2}\right) - \phi^{L_2}\left(\phi^{l_1} - \phi^{l_2+1}\right)\right) * \left(1 - \phi + \phi^{L_1+1}\left(\phi^{l_1} - \phi^{l_2}\right) - \phi^{L_2}\left(\phi^{l_1} - \phi^{l_2+1}\right)\right)\right\}. \tag{12}$$

It is convenient to prove Propositions 2(a) and 2(b) with Equation (11) and Propositions 2(c) and 2(d) with Equation (12).

According to Sirikasemsuk and Luong (2014), when $l_1 = l_2 = l'$, we have

$$BWEF_{\text{Model-B}}^{l_1=l_2=l'}(\phi, l', L_2) = 1 + \frac{2\left(1 - \phi^{l'+L_2}\right)\left(\phi - \phi^{l'+L_2}\right)}{1-\phi} \tag{13}$$

Proposition 2(e) can be proved with Equation (13). This completes the proof. □

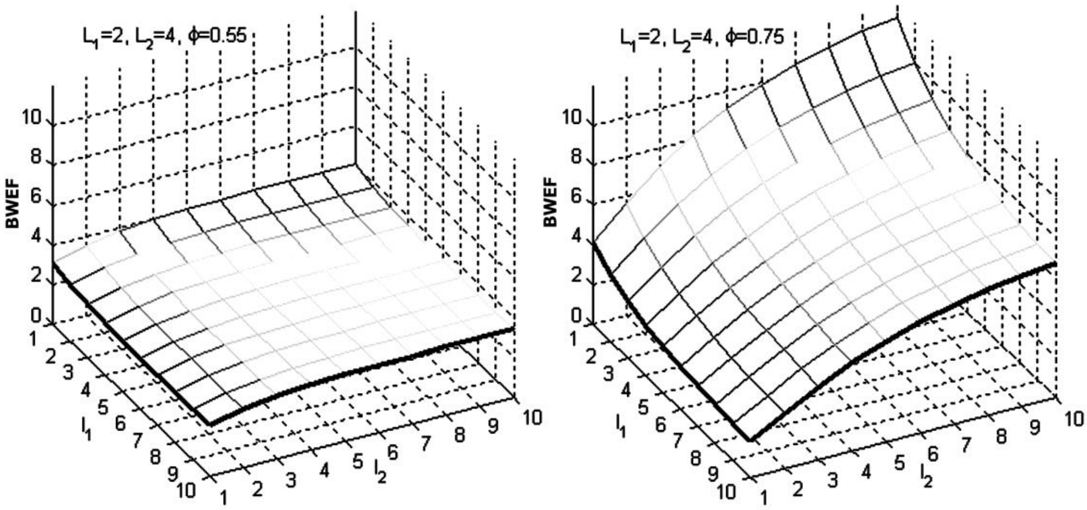

Fig. 3: Effect of lead time l_1 and l_2 on the bullwhip measure for Model-B (ϕ = 0.55 and 0.75).

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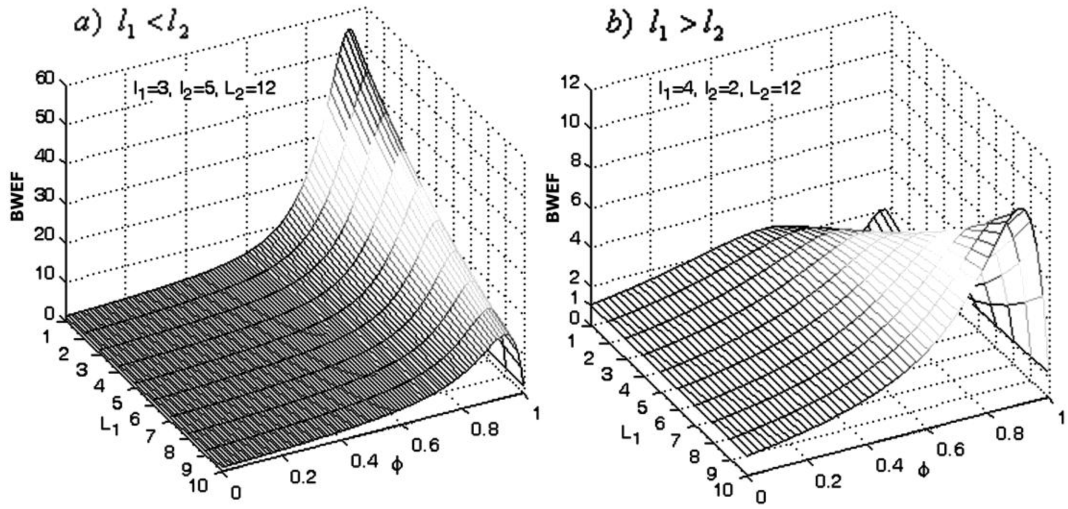

Fig. 4: Effect of lead time L_1 on the bullwhip measure for Model-B when L_2 = 12.

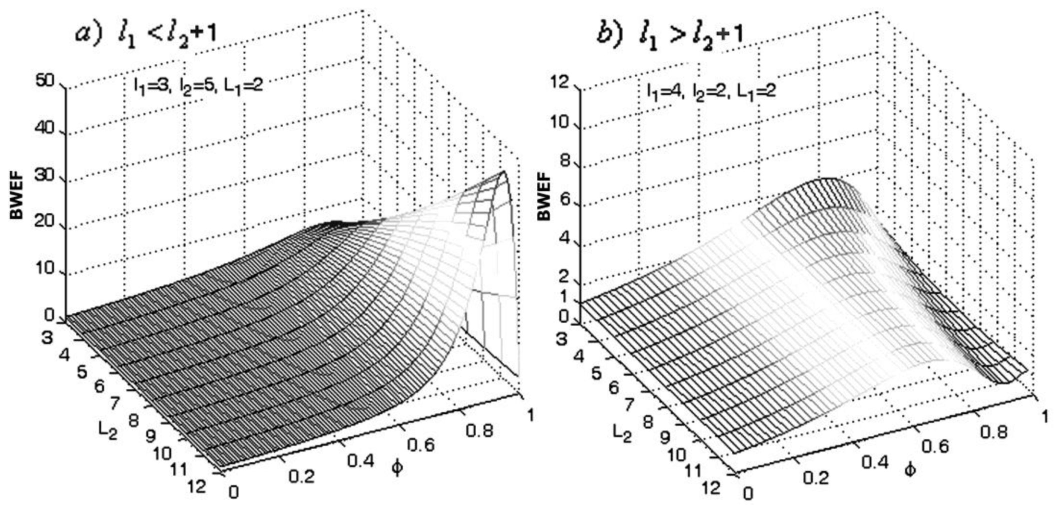

Fig. 5: Effect of lead time L_2 on the bullwhip measure for Model-B when L_1 = 2.

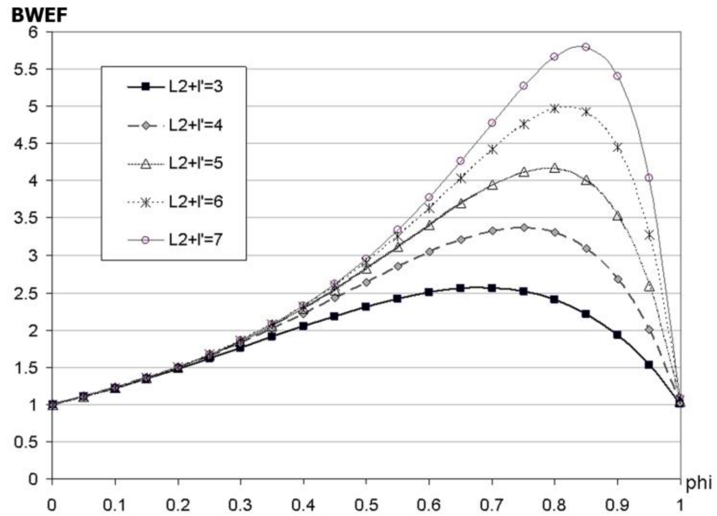

Fig. 6: Behavior of $BWEF_{\text{Model -B}}(\phi, l', L_2)$ for Model-B when $l_1 = l_2 = l'$.

From Proposition 2, although some lead times can be reduced to the minimum value of1, this does not mean that the BWEF would not occur. It should be noted that only conditions (7) to (9) for $0 > \phi > 1$result in the non-existence of the BWEF for Model-B.

Summary:

This research examines the dual-sourcing supply chain, consisting of one supplier, two distributors and one retailer, to demonstrate the influence the replenishment lead times have on the bullwhip effect (BWEF). The order-up-to level policy and the MMSE forecasting technique are used for the AR(1) model. This study is an extension of the research works on measures of the BWEF by Sirikasemsuk (2014) and Sirikasemsuk and Luong (2014) with an aim to investigate the impacts of increased and decreased lead times on the BWEF. The findings are as follows:

(1) for the identical lead times at the distributors-retailer links, the magnitude of the BWEFamplifies with increase in the lead times.

(2) for the unequal lead times at the distributors-retailer links ($L_1 < L_2$), the BWEFdoes not necessarily increase with increase in the lead times.However, the BWEF may decrease with longer lead times under certain conditions as detailed in this research.

From a managerial perspective, supply chain managers could gain from this research better insights into the impact of lead times on the BWEF under the dualsupplies environment. In improvement of supply chain efficiency, the managers may select to expend less time attempting to reduce lead times but more time analyzing and experimenting with other variables, e.g. information sharing, inventory policy and forecasting methods.

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