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Bullwhip Effect of a Closed Leep Supply Chain with and Without Information Sharing of Customer Demand

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BULLWHIP EFFECT OF A CLOSED LEEP SUPPLY CHAIN WITH AND WITHOUT INFORMATION SHARING OF CUSTOMER DEMAND

by

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ABSTRACT

BULLWHIP EFFECT OF A CLOSED LEEP SUPPLY CHAIN WITH AND WITHOUT INFORMATION SHARING OF CUSTOMER DEMAND

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In recent years, companies have become interested in a closed-loop supply chain that is concerned with the recovery pipeline. The expenses of a company can be influenced by large inventories and backlogs due to the bullwhip effect in the supply chain. Previous literature has shown that the bullwhip effect can be decreased by a reverse supply chain. This paper develops a closed-loop supply chain including seven echelons for recovery of end-of-life products. The model considers the order-up-to inventory policy and the exponential smoothing forecasting with a trend method in the system to assist in determining the ordering quantities. The best of the best is the method for this paper to choose a good smoothing parameter and to compare the necessity for information sharing. This test method provides the minimizing cost for the companies and analyzes the type of costs that can be reduced by selecting a good parameter value or utilizing information sharing. Furthermore, it also provides a way to reduce the bullwhip effect and verifies that the bullwhip index and cost are a complement to each other.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

1.1 Background

A forward supply chain is a term we call the classic supply chain, which focuses on the flow of raw materials, work-in-process, and finished products, and the flow of information from suppliers to the customers. In other words, we do not need to consider the subsequent processing of end-of-life products.

In recent years, the rapid growth of economics and industry has resulted in serious environmental pollution. Remanufacturing has become a popular strategy for extending the products' life. The strategy focuses on sustainability by reusing the products after the useful life of the products. The process of returning the product forms a reverse logistic. The reverse supply chain aims at the flow of reused items from consumers to producers. Combining the life process of the product and the useful life process of the product has another term, closed-loop supply chain. A closed-loop supply chain is a term first proposed by Guide et al. (2003): "The supply chain networks that include the returns processes and the manufacturer has the intent of capturing additional value and further integrating all supply chain activities."

Reused products decrease the waste of the products and prolong their lives. However, the reverse supply chain will cause other problems, such as the timing and the quality of the returned product. To ensure the reverse process is necessary for the supply chain network, researchers compared different performance results in the traditional forward supply chain and closed-loop supply chain. In addition to the total cost, decreasing the bullwhip effect is also an achievement for ensuring the performance of the profit.

Bullwhip effect is a common and significant phenomenon in supply chain management.

"Bullwhip effect" is a term described as a tiny fluctuation in demand in the orders of the customer that results in a drastically amplified fluctuation in demand in the upstream. Bullwhip effect is sometimes referred to as variance amplification, orders amplification, or the Forrester effect (Wang and Disney, 2016). It causes overestimates or underestimates customer orders and then leads to inventory backlog and shortage. Moreover, it also results in frequent fluctuation in production planning. Briefly, the bullwhip effect not only costs more but also leads to a poor relationship between customers and suppliers.

In order to avoid the shortage of the product, the companies need to prepare or store more inventory. The distortion of the orders' information results in the amplification of the orders from downstream to upstream. There is a large deviation between the amplified order and actual demand so that increases the total supply chain cost. According to Disney and Lambrecht (2005), not only the inventory difference but also the bullwhip index is able to be measured as a performance assessment for the profit.

The causes of the bullwhip effect can be mainly categorized into four reasons: demand forecast updating, order batching, price fluctuation, and rationing and shortage gaming (Lee, Padmanabhan, and Whang, 1997). One of the most significant is demanding forecast updating at each echelon of the supply chain network. The estimated demands can result in the companies storing more inventory to satisfy the demand and then increasing the holding cost.

In order to reduce the inefficient supply chain with too much inventory, researchers have been devoted to decreasing the bullwhip effect. To eliminate the bullwhip effect that is mainly caused by forecasted demand, some researchers aim at the lead time, information sharing, and policies' utilization. Chen et al. (2000) quantify the bullwhip effect and prove that a supply chain with centralized customer information can significantly reduce the bullwhip effect even though it cannot completely eliminate it. Disney and Towill (2003) consider lead time and propose that the vendor-managed inventory provides an opportunity to reduce the bullwhip effect. Paik and Seung-Kuk (2003) utilize statistical analysis to identify that the demand forecasting is one of the significant variables for bullwhip control and propose that information sharing is a necessary way for companies to avoid the safety of stock buildups. Yungao et al. (2012) analyze how the information sharing influences the bullwhip effect when using different ordering strategies with or without information at wholesalers. Tang and Naim (2004) also present the bullwhip effect with information transparency in manufacturing and remanufacturing systems.

Not only does information sharing help companies to reduce the distortion of the demand, but some literature also proposes that higher recovery rate and information transparency reinforcement alleviate the bullwhip effect. A higher percentage of the recovery will reduce the extent of the bullwhip effect (Xi and Xiao, 2015; Braz et al., 2018). The recovery process of end-of-life products includes the remanufacturing and refurbishing in the reverse system.

To consider a whole process that consists of the traditional supply chain and the process of recycling, the closed-loop supply chain can comprehensively consider them. Even when the product is redesigned as a recyclable product, the recycling rate is still low because of the lack of customer and manufacturer effort. A possible reason might be the unknown feedback on redesigning the supply chain. It is a challenge for persuading the companies to reform their process unless they know the profit of it. This background provides the motivation for the current research. We use multiple types of the recovery process, which consist of reusing, remanufacturing and refurbishing in the system.

1.2 Research objective

In this paper, we study a system with manufacturing and recovery options. Reusing, remanufacturing, and refurbishing comprise the recovery process. According to the background in the last section, the bullwhip effect will be influenced by the reforming system. Also, we need to prove the significance of the recovery process. This provides us a motivation for researching the degree of the difference of good solutions in different systems.

The objective of our research is examining the difference of the bullwhip effect between the models with and without information sharing in a closed-loop supply chain while the aim is to minimize system total cost. To be more specific, there are four objectives of this research.

(1) Find a good parameter value (smoothing parameter of level) of the exponential smoothing with a trend forecasting method.

(2) Examine whether the bullwhip effect is reduced by information sharing in the closed-loop supply chain when minimizing the total cost of the supply chain.

(3) Examine if the total cost is decreased by information sharing.

(4) Examine how the various types of costs are changed with information sharing.

We utilize the best of the best test to verify the performance of the model with information sharing and without information sharing, which will be detailed explained in Section 3. Briefly, we find the best result of minimizing the total cost in linear programming among the different values of the smoothing parameters. Furthermore, the purpose of this paper is to determine if the bullwhip effect is decreased by information sharing in the closed-loop supply chain. Moreover, we are also interested in knowing how types of costs are changed by information sharing.

The remainder of this paper is organized as follows. In Section 2, we review the literature related to the supply chain, the closed-loop supply chain, and the bullwhip effect. Section 3 describes the model and how we measure the bullwhip effect. Then, Section 4 discusses the best of the best test, chooses the result in our model, and further discusses more details. Last, the conclusion and future research are described in Section 5.

2. Literature Review

2.1 Supply chain

The organization of the supply chain consists of all indirect and direct parties and aims to satisfy the customers' demand. The structure of the supply chain is not only the supplier and the manufacturer, but also transporters, warehouses, and retailers. Within each organization, all the parts functions are involved in receiving and providing the customers' requests (Haniefuddin and Shamshuddin, 2013).

Supply chain management includes organizing the supply chain network. The strategic supply chain network is a key factor that influences the efficiency of tactical operations; hence the supply chain network has a long-lasting impact on the manufacturers (Hsu and Li, 2011). The supply chain network is a facility network that consists of supplying the material, producing the product, and transshipment of the product to the customer through the distribution system.

The objective of the supply chain management for the system is maximizing the companies' profit and fulfilling customer satisfaction. Abundant literature discusses the method of optimizing the network to fulfill the objective of supply chain management under different scenarios.

Bidhandi et al. (2009) proposed an integrated location and capacity choices model with a deterministic, multi-commodity, single-period to solve the supply chain network design problems. There are binary decision variables for the condition of opening the facility or not. Hence, to solve this problem, the authors utilized mixed-integrated linear programming with Benders' decomposition approach.

Tiwari, Chang, and Tiwari (2012) proposed a Highly Optimized Tolerance (HOT) algorithm based on a local incremental algorithm, power law, and control theory. HOT tried to get a better solution from each step of optimization. The algorithm is used for solving a multi-stage, multi-product supply chain network design problem. Peidro et al. (2010) also developed a fuzzy linear programming in a multi-echelon, multi-product, multi-level, multi-period supply chain network to solve the uncertain demand and supply.

Govindan et. al. (2015) improved the generic algorithm and used some aspects of particle swarm optimization as a hybrid algorithm. Then, they developed a deterministic multi-product, multi-echelon, multi-period model that considered the location and allocation in a closed-loop supply chain network and was undertaken using CPLEX and MATLAB software.

The possibility of disruption of the supply chain network design in the competition is demonstrated by Rezapour, Farahani, and Pourakbar (2017). They utilize an automobile supply chain case study to analyze the risk mitigation strategies in an acyclic supply chain with multiple suppliers, a single manufacturer, multiple retailers, and a single sale period.

Pham and Yenradee (2017) proved that the performance of the fuzzy model is better than that of the deterministic models for a manufacturing supply chain with a multi-echelon, multi-commodity, product structure, and manufacturing process. They utilized a combination of a bill of material and a process network to design a mixed-integer supply chain network. In addition, a real case study of a toothbrush supply chain is applied.

2.2 Closed loop supply chain

Transforming the waste from traditional garbage to new material or new utilization is a new tendency for enterprises. The linear economy dominated in a global economy in the past; however, it is not sustainable in the long-term. After the environmental awareness has been rising recently, a circular economy has risen for a sustainable business operation (Russo et al., 2019).

According to Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains definition, reverse logistics has changed again and again, but the source starts with a concept of "the wrong direction" (Rommert, 2004). Although some researchers discuss the forward and reverse supply chain separately, they need to be integrated since the network of them has influenced each other. Integrating the network of a forward supply chain and a reverse supply chain is a good way to avoid the separate design network, resulting in a suboptimal solution (Pishvaee, Farahani, and Dullaert, 2010; Pishvaee, Rabbani, and Torabi, 2011). Many researchers have shown an interest in integrating the supply chain. There are many reasons for considering the importance of the closed-loop supply chain and the necessary issue for the supply chain management because of rising customer awareness rising, implementation of environmental legislation, and the organizations' economical motivation (Soleimani and Kannan, 2015). Researching for sustainability in a supply chain has focused on the environment and operation management, including internal and external factors.

Some literature demonstrated that the network of the closed-loop supply chain is the key to optimizing the closed-loop supply chain (Pishvaee, Farahani, and Dullaert, 2010; Accorsi, Manzini, Pini, and Penazzi, 2015; Nidhia and Pillai, 2019). Earning a profit, reducing the total cost, and gaining customer satisfaction are important goals for a company.

A closed-loop supply chain network designed by mixed-integer programming model needs to be tradedoff between the transportation cost and fixed cost in Pishvaees' research (Pishvaee, Farahani, and Dullaert, 2010). They also proposed a bi-objective mixed-integer programming model to minimize the total cost and maximize the responsiveness of the integrated forward and reverse logistic network (Pishvaee, Rabbani, and Torabi, 2011).

Özceylan and Paksoy (2013) also developed a multi-parts and multi-period mixed-integer programming model to optimize the distribution and production planning with deterministic demand for an integrated supply chain.

A closed-loop supply chain including reuse, refurbish, recycle and disposal of parts is proposed by Jindal and Sangwan (2014). They used a fuzzy mixed-integer linear programming model to maximize the total profit through optimally deciding the number of parts to be purchased from multiple suppliers and the part quantities to be processed at a reverse supply chain facility.

Saha, Asadujjaman, and Asaduzzaman (2017) developed a single-product multi-period mixed-integer linear programming model general closed-loop supply chain that consists of a manufacturing plant, a distribution center, and a customer. The demand is deterministic and unlimited capacity of the facility in the model. The objective is minimizing cost and determining the optimum facility location with the optimal network flow.

The closed loop supply chain with a single period also helps to control the expiration cost and waste of emergency medicine by optimal ordering policy called a hysteron-proteron scheme (Pan et al., 2018).

2.3 Bullwhip effect (BWE) in the closed loop supply chain

The bullwhip effect was first proposed in Industrial Dynamics by Forrester (1961). It is a phenomenon that results in inefficiencies in the supply chain by forecasting when there is a tiny fluctuation in demand in the downstream, along with a drastically amplified fluctuation in demand in the upstream. The uncertain demand results in the problem of product storage and surplus and then increasing the cost of inventory. The amplification phenomena of the supply chain in the different rates of manufacturers, suppliers, retailers, and customers is called the bullwhip effect.

It also proved the existence by a beer game since Sterman (1989) presented it. The experiment processed by cosplaying a four-stage supply chain, including factory, distributor, wholesaler, and retailer. The characters have to place orders to upstream after accepting the orders from downstream. However, the only information is the orders from downstream instead of any other information sharing. As a result, the simulation displayed that the small fluctuation in orders of the customer causes large vibrating in upstream inventories and orders.

Much literature has been devoted to researching several ways to reduce the effect of the bullwhip. Chen, Ryan, and Simchi-Levi (2000a) quantify the bullwhip effect by moving an average forecast method in a two-stage supply chain including a retailer and a manufacturer. They also compared and proved that a centralized supply chain can reduce the bullwhip effect but not completely eliminate it. Then, they proposed the exponential smoothing forecast method to quantify the bullwhip effect in the same year (Chen, Ryan, and Simchi-Levi (2000b). Also, they compared the result of variability in the moving average method and the exponential smoothing method.

Gearya, Disney, and Towill, (2006) classified ten principles, control system, time compression, information transparency, echelon elimination, synchronization, multiplier, demand forecast, order batching, price fluctuation, and gaming principles, to reduce the BWE and presented that they can be eliminated through reengineering the supply chain.

In the as-usual supply chain, the manufacturers, suppliers, and retailers coordinate to balance the inventory to avoid the dynamics of inventory and increase of the cost. Although the cause of the bullwhip effect in the forward supply chain is similar to those in the closed loop supply chain, however, the bullwhip effect could be reduced in the closed-loop supply chain. Many works of literature mentioned that as the recovery percentage of product recycling improves, the bullwhip effect diminishes; as the recovery percentage of product recycling decreases, the bullwhip effect enhances.

Özceylan and Paksoy (2013) experimented with the cost change for different collection rates. It showed that the fixed cost did not change but the purchasing cost decreased as the collection rates increased from 5% to 50%. Ma et al. (2014) proved that the reverse supply chain can reduce the bullwhip effect, which is more obvious as the higher return rate. However, the bullwhip effect cannot be eliminated. The manufacturing bullwhip effect increases due to the number of echelons increasing. Xi and Xiao (2015) proposed that if the percentage of recycler recovery increases, the bullwhip effect will diminish and the quantity fluctuations of other stages will reduce.

On the other hand, lowering the recycled parts of the recyclers proportion will enhance the bullwhip effect and the inventory fluctuation for manufacturers and two retailers. Sadeghi (2015) considered the bullwhip effect in the two-product supply chain with an exponential smoothing forecast method. Then, he compared a moving average method and an exponential smoothing method. The result is as the same as in previous literature, in which the bullwhip effect of exponential smoothing is less than the other. Furthermore, he made the conclusion that the changed demand process coefficient will influence less or more bullwhip effect.

Wang and Disney (2016) reviewed the bullwhip literature by empirical, experimental, and analytical methodologies. The terms of demand, delay, forecast, replenishment policy, and coordination strategy are considered in the previous literature. Those methods can actually help to decrease the bullwhip effect. Hence, we focused on reviewing how ordering policy, forecasting, and information sharing strategy affect the consequence of the bullwhip effect and costs. Le et al. (2017) discussed how the product exchange policy plays an important role in decreasing the bullwhip effect. The product exchange policy with uncertain demand, recycling, and remanufacturing quantities decreases the bullwhip effect for the distributor and the retailer, and decline in the bullwhip effect of the manufacturing is gradually larger than the retailer and the distributor. Braz et al. (2018) reviewed how the closed-loop supply chain affects the dynamics of inventory and decreases the bullwhip effect; at the same time, the model considers environmental protection.

The cause of the BWE could separate into four parts, demand signal processing, rationing game, price variation, and order batching (Keshari et al., 2018.) Dominguez et al. (2019) also mentioned that the most research efforts of managing the closed-loop supply chain impact are (1) quantity of the returns, (2) reverse logistics operation time, and (3) transparency of information. They focused on analyzing the bullwhip effect that considers the dynamic behavior of the closed-loop supply chain by considering variability in the remanufacturing lead times. The result is lead-time paradox, which mentioned that CLSCs may benefit from an increase in the remanufacturing lead time in the dynamics of such systems. They also considered the OUT inventory policy that will reduce the performance of inventory, which will yield higher return quantity or longer and variable remanufacturing lead time.

According to a comprehensively optimal closed-loop supply chain, the paper designed a model with order-up-to inventory policy and exponential smoothing with trend forecasting technology in the periodic inventory review system to minimize total cost and decrease the bullwhip effect in the closed-loop supply chain network.

2.4 Inventory policy in a supply chain

Period review policy is comprehensively utilized in real-world nowadays for the forward supply chain. It is a popular inventory policy in the practical supply chain and the supply chain literature (Dejonckheere et al. 2003; Wang and Disney, 2016; Ma et al., 2018). Furthermore, the higher efficient comparing to continuous inventory review policy for adjusting replenishment time. Although a (R, S) policy incurs higher holding costs than (R,Q) policy, it is easier to administer than the continuous review policy and more often used by the companies. Navin, Shankar, and Choudhary (2017) propose that period review system have better perform than a continuous review system in the condition of a higher returned product rate and review period. This research adopts the periodic review policy of inventory policy in the supply chain.

2.5 Demand process in SC

Customer demand has been modeled as a nonstationary process or a stationary process. The characteristic of the stationary demand process includes long run and variance and mean are determined such as the demand with normal distribution. On the opposite hand, the non-stationary process is a random generation without any deterministic trend. The probability distribution of the demand changes over time and is only partially observed through the actual demand values. Furthermore, the mean and variance in the stationary process is not related to the time series. Most of literature including So and Zheng (2003), Agrawal, Sengupta, and Shanker (2009), and Costantino et al. (2015) assumed the demand as the stationary process and autoregressive demand process. This research adopts the stationary process of demand from customers.

2.6 Forecasting

To reduce the bullwhip effect, one of the most important methods is utilizing a good forecasting technique since the forecasting method is highly related to the inventory system of the supply chain. Generally, forecasting techniques and methods can be separated into four types, judgement methods, time-series methods, market research methods, and causal methods. In this paper, we consider the time-series method to forecast. The time series forecasting method is a mathematical method including moving average, exponential smoothing, regression analysis, and many more, which are utilized by past information. Some researchers considered different time-series forecasting methods to predict the demand, including exponential smoothing forecasting method, minimum mean square forecasting method, and simple moving-average forecasting method (Ma et al., 2013; Sedaghi, 2015; Sabbaghnia, 2018).

Moving average is a kind of forecasting technique that needs abundant historical demand information but a small lead time. If we use a moving average, it will ignore the trend of demand. Moreover, the moving average does not consider lead time. Lead time is a vital factor for inventory and shortage of product. Ignoring the distributor's message flow time, the lead time will be changed.

On the other hand, the exponential smoothing forecasting methods assign weights to current demand and previous forecasts to arrive at new forecasts. Chen et al. (2000) demonstrate that some demand processes, i.e., independent and identically distributed, demands or demands with a linear trend, and exponential smoothing forecasting method, will result in larger variability than using a moving average forecasting method. Although the exponential smoothing forecasting method might not be the best forecasting technique, it is certainly a common technique used in practice. Wright and Yuan (2008) forecast the future demand by Holt's exponential smoothing and determined the smoothing constant for the data and trend based on historical data by minimizing the mean-square error (MSE). Moreover, they concluded that both Holt's and DES forecasting methods can reduce the bullwhip effect. Bayraktar et al. (2008) considered the exponential smoothing forecasting of linear seasonal demand with different smoothing parameters. They also concluded that the bullwhip effect is compensated for by the variability generated by seasonality. Peng et al. (2015) compared the single, double, and triple exponential smoothing method and proposed that exponential smoothing with a trend gives a better forecast for demand.

In this study, we focus on the exponential smoothing forecasting method with a trend to predict the orders of the customer and orders of the manufacturing site. According to Wright and Yuan (2008), the bullwhip effect can be alleviated in a smaller value of a smoothing constant for data and trend. Researchers usually discussed a good smoothing parameter from historical data of exponential smoothing method. Hence, this research adopts the exponential smoothing forecasting with the trend as the forecasting technique and then finds a good smoothing parameter in the supply chain.

2.7 Information sharing

The literature indicated the quite high value of demand information sharing, especially as demands are significantly correlated over time (Lee et al., 2000). To prevent the prediction error of production, information sharing is an effective element to consider in modeling. Agrawal et al. (2009) proved the decreasing of inventory cost by combining the information sharing and ordering policy. Sharing information in the supply chain is also a method of reducing the shortage of products. Moreover, sharing only inventory information and capacity information instead of demand would result in magnifying the bullwhip effect (Yu et al., 2010). According to Zhao et al. (2018), the information sharing is sharing the sales information from retailers that is the closest stage to the customer in the supply chain. They also proved that information transparency reinforcement can decrease the bullwhip effect largely by a system dynamic method. It is worth mentioning that distributors prefer to decrease the bullwhip effect by reducing prediction time instead of information sharing. Disney and Towill (2003) proposed another type of information sharing, i.e. the vendor management inventory, which utilizes information sharing to achieve the centralization strategy. In this research, we achieve information sharing through which the manufacturer can directly obtain customer demand, which will be explained in detail in Section 5.

3. Research Methodology

In this research, we check if the bullwhip effect (BWE) is decreased by information sharing in a closed-loop supply chain. We use an example to find the BWE in a CLSC and use an LP modeling for the decisions of the CLSC. Moreover, the performance will be compared by the best of the best test.

3.1 Product disassembly schematic

The supply chain deals with a product that has two types of components: com1 and com2. One unit of a product consists of *a* unit of com1 and *b* unit of com2. For example, the product can consist of 2 units of com1 (*a* =2) and 4 units of com2 (*b*=4). Figure 1 illustrates a possible product and its components.

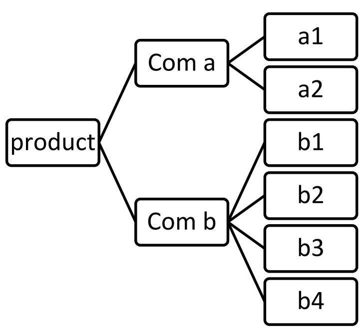

Figure 1. Schematic diagram of the relationship between products and components.

In this research, the products will be disassembled at the disassembly center in the reverse process of the supply chain. We assume that all of the successfully disassembled components can be refurbished. That is to say, once the products are successfully disassembled at the disassembly center, the components of these products can be shipped to the refurbishing center. E.g., there are 10 units of products successfully disassembled, the refurbishing center can obtain 20 units of the

Com a. all of 20 components can be shipped to the refurbishing center. There is no component to be disposed of as long as the product is successfully disassembled.

The refurbished components can be shipped to the manufacturing site and can be produced to a new product at the manufacturing site. The combination method is also based on Figure 1. 2 units of Com a and 4 units of Com b can be produced into 1 unit of product at the manufacturing site in this research. This is the explanation of the relationship between the products and the components in this research.   We use an example to find the bullwhip effect in a CLSC in this research. We will discuss a detailed example in Section 4.1.

3.2 Performance comparison method

One of the objectives in our research is checking whether BWE is reduced by information sharing in CLSC when minimizing the total cost of the supply chain; we utilize the best of the best test to evaluate the performance. There are two tests for evaluating the performance of two methods, the best of the best test and the territory test that was first proposed (Xi and Jang, 2012).

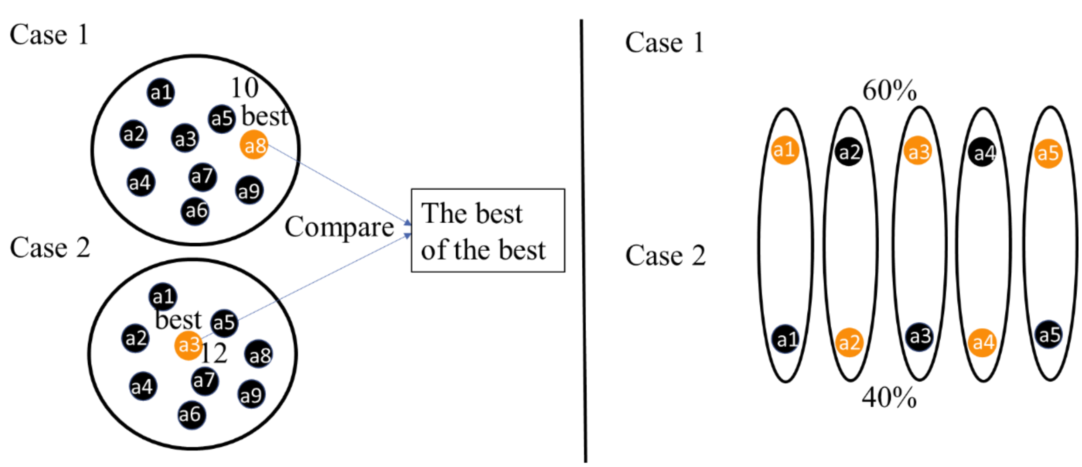

Figure 2. performance comparison methodology -Best of the best test and Territory test.

Figure 2 illustrates the schematic figure of two tests. In both tests, we compare the BWE of two cases that are the model with IS and the model without IS. We utilize linear programming to optimize the function and minimize the total cost. In the best of the best test of this figure, we have 9 results of minimum total cost in both case 1 and case 2. a8 has the minimum total cost among all of the total cost in 9 results in case 1 so we chose it in case 1, and the minimum total cost is 10; in case 2, the minimum total cost is 12 in a3 so we chose a3 as the best result of minimizing total cost in case 2. Because the result of minimizing total cost in case 1 is smaller than the result in case 2, we know a8 in case 1 is the best of the best.

In the territory case, case 1 and case 2 possess 5 results of minimum total cost separately. They compare each other and find the smaller result of minimizing the total cost. For example, the total cost of a1 in case1 is 1, the total cost of a1 in case 2 is 2, so we mark a1 in case 1 because it is smaller. After comparing all of the results between case 1 and case 2, the better result of minimum total cost in case 1 occupies 60%, and the better result of minimum total cost in case 2 occupies 40%, so case 1 is better.

In this research, we utilize the best of the best test because we have the objective of the research that knowing the good parameter for reducing total cost and knowing if information sharing can reduce the BWE. We utilize the best of the best test to choose the best result of minimizing total cost and knowing if information sharing can reduce the BW index.

4. Supply Chain Model

4.1 The example case considered

We developed a model for the closed-loop supply chain system that contains the returned product from the customer and then starts the recycling process. In this model, we take the solar panel as an example. The solar panel is the product, and then the aluminum frame and the silicon wafer in this panel can be the components.

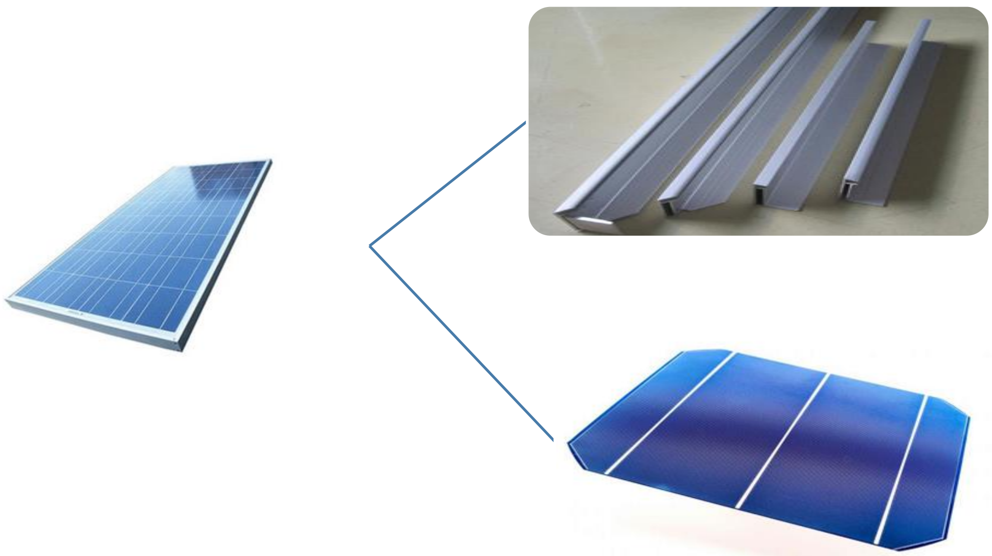

Figure 3. From left to right, from top to bottom is a solar panel, aluminum frames, and silicon wafers respectively. (Graph by: mrsolar.com, Physorg, IndiaMART.)

We called the aluminum frame and the silicon wafer i1 and i2 in our model. The properties of remanufactured wafers are almost identical to those of commercial virgin wafers (Shin and Park, 2017). Hence, we assume the remanufactured product's quality is as good as a new one.

In our model we assume that the solar panel that is returned by the customer is 60 % of the actual shipped solar panel that was sold to the customer at the end of the previous period. Furthermore, 30% of the returned solar panels can be reused directly after being identified from the collection center. On the other hand, 70% of the returned solar panels will be shipped to a disassembly center and will be disassembled to 1 unit i1 and 10 units i2. At the disassembly center, 10% of the two components would be disposed and 90% of the i1 and i2 successfully disassembled would be shipped to the refurbishing center. Eventually, all of disassembled i1 and i2 will be refurbished at the refurbishing center. To be noticed, the actual disassembly quantities and actual refurbishment quantities must less than 3000 units, which is the maximum rate of disassembling and refurbishing respectively per time.

4.2 Problem description

The supply chain consists of a single-product, multi-echelon, and two-direction flow, which are forward supply chain and reverse supply chain. The forward supply chain includes an external supplier, a manufacturer, a distribution center, and a customer market. The reverse supply chain includes a collection center, a disassembly center, and a refurbishing center. In total, there are 7 echelons in the closed-loop supply chain.

External supplier

The external supplier has an unlimited supply.

Manufacturer

The manufacturer knows the volume of refurbished components that will be shipped to the manufacturing site from the refurbishing center in the next period, e.g., at the beginning of period 7 and knows the component quantities to be delivered from refurbishing center to the manufacturing site at the end of period 7. He orders the components from the external supplier to satisfy the production quantities at the manufacturing site. If the quantities of the refurbished components shipped to the manufacturing site from the refurbishing center are delivered beyond the quantity needed, they are stored at the manufacturing site. Orders placed by the manufacturer that are sold from an external supplier are received immediately.

The manufacturer forecasts the demand for the distribution center and decides the product quantities needed to be produced at the end of the period. There is a production lead time that has to be considered but we do not consider the shipment lead time here. The shipment lead time from the manufacturing site to the distribution center is 0. (E.g., as the manufacturer forecasts the distributor's demand during period 3, he produces up to a volume at the manufacturing site during period 2 and the products are available at the distribution center at the beginning of period 3 since the shipment lead time is 0.) When there is a difference between the distributer's demand at the next period predicted from the manufacturer and the actual demand of the distributor, there are inventories or backorders at the manufacturing site. Any unfilled demand is backlogged in our model.

Distributor

The distributor places the order to the manufacturer at the end of the period after the distributor knows the quantities of returned products will be shipped to the distribution center at the end of the period. (E.g., if the distributor knows some products will be delivered that were shipped from the collection center at the end of period 5, he decides the quantities of products needed to be ordered from the manufacturer at the end of period 5 that will also be delivered at the end of period 5.) That is to say, the distributor receives the products from two different sources and orders from the manufacturing site and reused products from the collection center.

Similar to the manufacturing site, if there is a difference between actual orders of the customer and the predicted demand of customers at the next period by the distributor, there are inventories or backorders at the distribution center. When the customer places the order for the distribution center, the distributor would provide the products to the customer after distributing and shipping the product for a lead time. (E.g., if the distributor knows the customer demand is 300 during the period 4, they would distribute and ship the product at the end of period 3.)

Customer

Customer demand is generated by a stationary process that follows the constant normal distribution N~ (500,100).

Collection Center

There are two flows for the sold products in this paper. (1) The sold product in the forward supply chain. (2) The exhausted, damaged, or unwanted product that is called the returned product and would be returned to the collection center.

The returned products would be collected at the collection center by the customer so we do not consider the shipment lead time here. There is a deterministic percentage relationship between the actual shipped products from the distribution center to the customer at the previous period and returned products. (E.g., if the returned rate is 0.2, the returned products at the end of period 5 are 20 percent of the actual shipped products from the distribution center to the customer at the end of period 4.)

The returned products would be classified as reused products and the products that are to be disassembled. We also assume a percentage relationship between returned products and reused products. Also, the reused products would be shipped and become the accessible inventories at the distribution center and could be sold to satisfy customers immediately. (E.g., if the reused rate is 0.3, the reused products at the end of period 5 are 30 percent of the returned products at the end of period 5.) Other returned products would be shipped to the disassembly center at the same time. (Continuing with the previous example, the returned products are shipped to the disassembly center at the end of period 5.)

Disassembly Center

The disassembly center receives the product from the collection center and then disassembles the products for a lead time of 1 week to components and ships to the refurbishing center. We assume a constant rate of disassembling at the disassembly site. If the products are to be disassembled beyond the rate of disassembly, there will be product inventories at the disassembly center. The remaining products are identified as defective products and will be disposed of.

Refurbishing Center

The components received from the disassembly center would be refurbished at the refurbishing center. Then they would be shipped to the manufacturing site for a shipment lead time of 1 week. (E.g., if the parts are disassembled and shipped from the disassembly center at the end of period 5, these parts can be refurbished and shipped to the manufacturing center at the end of period 6.) There is also a constant percentage of successful refurbishment. If the quantities of the components shipped from the disassembly center to the refurbishing center exceed the refurbishing rate that can be loaded in the refurbishing center, there are inventories of components at the refurbishing center.

The refurbished components will be shipped to the manufacturing center and turned into usable inventories of parts that can be produced to products at the manufacturing site. The quality of refurbished components is as same as new components ordered from the external supplier. Within each period, inventory in the system is considered at the beginning of each period. The shortage, shipment, and orders in the system are known at the end of each period.

4.3 Periodic inventory review policy in the model

In our research, both the distribution center and the manufacturing site follow a periodic review policy for reviewing their inventories and utilizing stock for replenishment. According to the periodic inventory review policy, the inventory level would be reviewed periodically to determine suitable quantities to order. The suitable quantities are determined by order-up-to policy to stock the level to the target level. The person who ordered places the order such that the inventory on hand and to be delivered orders sum to the order-up-to-level. To avoid the inventory used exhaustedly during the lead time, a safety stock is considered. The safety stock depends on the service level selected from the provider. The higher the service level, the higher the inventory level; on the contrary, the lower the service level, the lower the inventory level. Last, the order-up-to-level is determined by the orderers forecast and safety stock. The forecasting will be discussed more in the next section.

The distribution center determines an order-up-to-level during the period based on the expected orders of the customer during the period and some safety stock. (E.g., the distributor expects the orders of the customer during period 7 and determines the order-up-to level of period 7 at the end of period 6.) On the other hand, the manufacturer produces the product according to the order-up-to level at the end of each period. We call it "produce-up-to level." The produce-up-to level is based on the expected orders from the distributor at the end of the period and the safety stock. (E.g., the manufacturer expects the orders at the end of period 7 from the distributor and determines the produce-up-to level of period 7 at the end of period 6.)

4.4 Exponential smoothing forecasting with trend

Both the manufacturer and the distributor predict the demand for downstream. Effective forecasting can precisely calculate the demand and decide the order-up-to-level. To be more specific, precise forecasting can reduce the risk of shortage and reduce cost requirements. We use the exponential smoothing forecasting with trend as a forecasting technique for incoming orders of the manufacturer and distributor. The exponential smoothing forecasting with trend consists of the estimated demand level and the trend of the estimated demand of the downstream. The estimated demand level includes the previous estimated level and the orders from the downstream echelon. The estimated demand trend consists of the previously estimated demand trend and the difference between the estimated level in the current period and the previous period.

The distributor expects the orders of the customer at the end of the period through the previous orders of the customer and the historical trend of demand. Similarly, the manufacturer expects the orders from the distributor at the end of the period through the orders in the previous period and the orders in history trend.

4.5 Closed-loop supply chain model

The overall system of the model is shown in Figure 4.

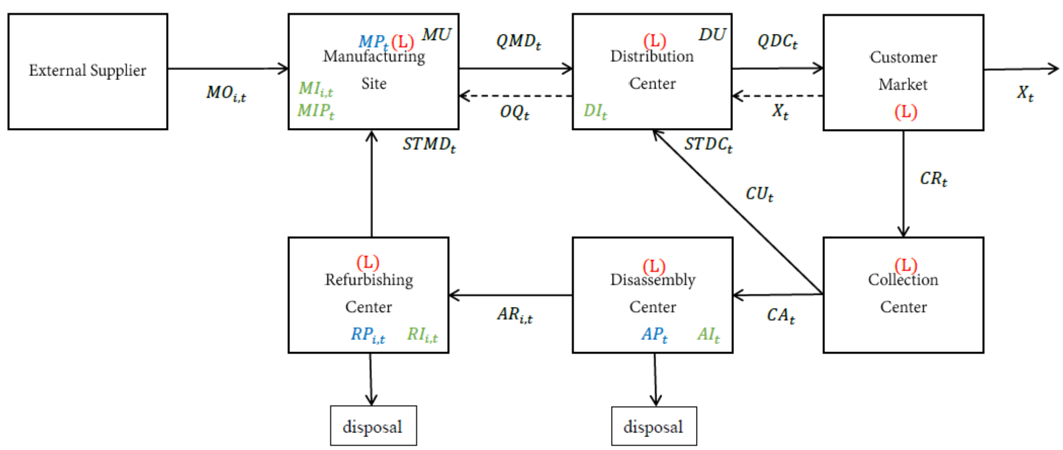

Figure 4. The proposed closed-loop supply chain framework.

The assumption used in developing the model are as follows:

- We did not consider consumption lead time in the modeling. As Cannella, Bruccoleri, and Framinan (2016) mentioned, products would be held by customers for a time known as "consumption lead-time."
- Demand of the customers is uncertain. We model the customer demand with a normal distribution with a linear tread of the mean of the distribution.
- Shortage is allowed and backlogged if an echelon (Manufacturing Site or Distribution Centr)

faces shortage in a period.

- There is a production lead time of the manufacturing site, operation lead time at the distribution center, collection center, disassembly center, and refurbishing center. Lead time = 1 week
- The initial inventory of the manufacturing site and distribution center is known.
- Return rate, reused rate, and disposal rate are constant.
- Production cost is known.
- Transportation cost is known.
- Inventory cost is known.
- Shortage cost is known.
- The quality of the reused product is as good as the new product
- Shipment capacity is unlimited.
- Shortage capacities are unlimited.

4.6 Notation definition

Set of indices

t	number of period t	$t = 1, \dots, T$
i	part type i of the product	$i = 1, \dots, N$

Objective function cost coefficients

MPC	Production setup cost
SPC	Unified shipping cost from each site to the next site
ODC	Ordering cost from the external supplier
IC	Unified inventory holding cost at each site except collection center

STC Shortage cost at manufacturing center and distribution center

Parameter

MC Maximum production rate

DC Maximum rate of disassembling

AC Maximum rate of the disassembled product

RC Maximum rate of the refurbished product

z Service level (target probability of no shoratge at distribution center)

α Smoothing constant for the level of the series of the forecasting model

β Smoothing constant for the trend of the forecasting model

b A constant return percentage for the sold product

d A constant reuse percentage for the returned product

s A constant successful disassembly percentage for the shipped product from the collection center

f_i A constant successful refurbish percentage for the disassembled part i from the collection center

X_t Customer demand which is also the orders of the customer during period t. Randomly generted from a normal distribution

a_i Number of units of part i of the product

Decision variable

MU_t Produce-up-to level of product at manufacturing site at the end of period t

MP_t Production quantity, which is also the orders of the manufacturing site, of product at the manufacturing site during period t.

$MI_{i,t}$	Inventory of part i at manufacturing site at the beginning of period t
MIP_t	Inventory of product at manufacturing site at the beginning of period t
$MO_{i,t}$	Ordeing quantity of part i by manufacturing site at the end of period t
MF_t	Forecasting demand from distribution center during period t
ML_t	Estimate of the level for distribution center during period t
MT_t	Estimate of the trend (slope) for distribution center during period t
QMD_t	Actual delivered quantity from manufacutring site to distribution center at the end of period t
$STMD_t$	Product shortage at manufacutring site at the end of period t
DU_t	Order-up-to level of product at distribution center at the end of period t
DI_t	Inventory of product at distribution center at the beginning of period t
OQ_t	Demand for manufacutring site from distribution center during period t
DF_t	Forecasting customer demand during period t during period t
DL_t	Estimate of the demand level for customer market during period t
DT_t	Estimate of the trend (slope) for customer market during period t
QDC_t	Actual quantity can be sold to customer at the end of period t
$STDC_t$	Product shortage at distribution center at the end of period t
CR_t	Returned product quantity during period t
CU_t	Quantity of product to be reused, and shipped to distribution center at the end of period t
CA_t	Quantity of product to be disassembled, and shipped to disassembly center at the end of period t
AI_t	Inventory of product at the beginning of period t

AP_t Disassembling quantity of product at disassembly center during the period t

APS_t Disposal product at disassembly center at the end of period t

$AR_{i,t}$ Quantity of part i shipped from disassembly center to refurbishing center at the end of period t

$RPS_{i,t}$ Disposal part i at refurbishing center at the end of period t

$RI_{i,t}$ Inventory of part i at refurbishing center at the beginning of period t

$RP_{i,t}$ Quantity of part i refurbished successfully and shipped from disassembly center to refurbishing center at the end of period *t*

4.7 Model objective function

The objective of the linear programming model is minimizing the total cost in a closed-loop supply chain. **The cost minimization function** shows in Eq. (1).

$$\text{Min cost} = \sum_i \sum_t \text{shipping costs}_{i,t} + \sum_t \text{production costs}_t + \sum_i \sum_t \text{ordering costs}_t + \sum_i \sum_t \mathit{inventory\ costs}_{i,t} + \sum_t \text{shortage costs}_t \quad (1)$$

The formula of the shipping cost is shown in Eq. (2)

$$\sum_i \sum_t \text{shipping costs}_{i,t} = \text{SPC} * \sum_i \sum_t (QMD_t + QDC_t + CU_t + CA_t + AR_{i,t}) \quad (2)$$

Where SPC is the unified shipping cost for each site while considering shipping cost. QMD_t is the actual delivered quantity from the manufacutring site to the distribution center at the end of period t. QDC_t is the actual quantity that can be sold and shipped to the customer market at the end of period t. CU_t is the quantity of the product to be reused, and shipped to the distribution center at the end of period t. CA_t is the quantity of the product to be disassembled, and shipped to the disassembly center at the end of period t. $AR_{i,t}$ is the quantity of part i shipped from the disassembly center to the refurbishing center at the end of period t.

The formula of production cost in Eq. (3)

$$\sum_t \text{production costs}_t = \text{MPC} * \sum_t MP_t \tag{3}$$

Where MPC is the production setup cost at the manufacturing site and MP_t is the producing quantity of the product at the manufacturing site during the period t

The formula of ordering cost in Eq. (4)

$$\sum_i \sum_t \text{ordering costs}_t = \text{ODC} * \sum_i \sum_t MO_{i,t} \tag{4}$$

Where ODC is the ordering cost for ordering from the external supplier. $MO_{i,t}$ is the ordering quantity of part i by the manufacturing site at the end of period t.

Inventory cost function is shown in Eq.(5)

$$\sum_i \sum_t \text{inventory costs}_{i,t} = \text{IC} * \sum_i \sum_t (MI_{i,t} + MIP_t + DI_t + AI_t + RI_{i,t}) \tag{5}$$

Where IC is the inventory cost for every single site. $MI_{i,t}$, and $RP_{i,t}$ is the inventory of part i at the manufacturing site and the refurbishing center at the beginning of period t. $MIP_t, DI_t,$ *and* AI_t is the inventory of product at the manufacturing site, distribution center, and disassembly center separately at the beginning of period t.

The shortage cost function is below.

$$\sum_t \text{shortage costs}_t = \text{STC} * \sum_t (STMD_t + STDC_t) \tag{6}$$

Where STC is the shortage cost at the manufacturing site and distribution center. $STMD_t$ *and* $STMD_t$ are the product shortage at the manufacturing site and distribution center at the end of period t.

4.8 Modeling

4.8.1 Forecast

In the exponential smoothing method with trend, the forecasts are determine by Eq. (7)

$$F_t = LV_t + T_t \tag{7}$$

where F_t is the forecast for period t, LV_t is the estimated constant demand level at period t, and T_t is the estimate of trend at period t.

Equation of LV_t and T_t are showed as follow.

$$LV_t = \alpha * D_{t-1} + (1 - \alpha) * LV_{t-1} \tag{8}$$

$$T_t = \beta * (LV_t - LV_{t-1}) + (1 - \beta) * T_{t-1} \tag{9}$$

in which $0< \alpha < 1$ and $0< \beta < 1$ are smoothing constants, D_t is the customer demand. It should be noted that the current forecast level LV_t is the weighted average of the previous period's demand and the previous forecast demand level. The current trend of the forecast T_t is the weighted average of the difference between the current forecast level and the previous forecast level plus the previous forecast trend. Eq. (8) and Eq. (9) substitute for Eq. (7) and can be obtained as below.

$$F_t = \alpha * D_{t-1} + (1-\alpha) * LV_{t-1} + \beta * (LV_t - LV_{t-1}) + (1-\beta) * T_{t-1} \quad (10)$$

If we apply this formula to our model, the orders of the customer forecasted by distributor (DF_t) and the distributor demand forecasted by manufacturer (MF_t) in this research is below.

$$DF_t = \alpha * X_{t-1} + (1-\alpha) * DL_{t-1} + \beta * (DL_t - DL_{t-1}) + (1-\beta) * DT_{t-1} \quad (11)$$

$$MF_t = \alpha * OQ_{t-1} + (1-\alpha) * ML_{t-1} + \beta * (ML_t - ML_{t-1}) + (1-\beta) * MT_{t-1} \quad (12)$$

4.8.2 Order-up-to level

In the model, the distributor and manufacturer follow an order-up-to (OUT) inventory policy to order and produce the products. We assume the safety stock in the produce-up-to level at the manufacturing site at the end of the period is 10 percent of the expected demand from the manufacturer for a distributor during the period.

And the order-up-to level at distribution center at the end of the period is the expected orders of the customer during the period plus the safety stock, which is the service level times the standard deviation of the orders of the customer.

$$MU_t = 1.1 * MF_t \quad (13)$$

$$DU_t = DF_t + z * \sigma X_t \quad (14)$$

Where MU_t and DU_t are the order-up-to level used for considering the ordering quantities at the manufacturing site and the ordering quantities at the distribution center. z is a constant service level that is the product of z-score (e.g., 1.65 for 95% service level). σX_t is the standard deviation of customer demand that follows the normal distribution N~(500,100).

4.8.3 Inventory balance

If the production is more than the distribution center's demand, there is inventory at the manufacturing site at the beginning of the period shown as Eq. (15). On the other hand, if the quantities of actual shipped product for the distribution center cannot satisfy the request from the distribution center, there is a shortage of product at the manufacturing site at the end of the period shown as Eq. (16).

$$MIP_{t+1} = MIP_t + MP_t - QMD_t \qquad (15)$$

$$STMD_t = STMD_{t-1} + OQ_t - QMD_t \qquad (16)$$

In equation (15), the inventory of the product at the beginning of the period is the previous inventory of the product at the beginning of the period plus previous orders of the product at the manufacturing site during the period minus the actual shipped product to the distribution center at the end of the period. Figure 5 demonstrates the schematic diagram of the product's inventory balance equation at the manufacturing site, Eq. (15).

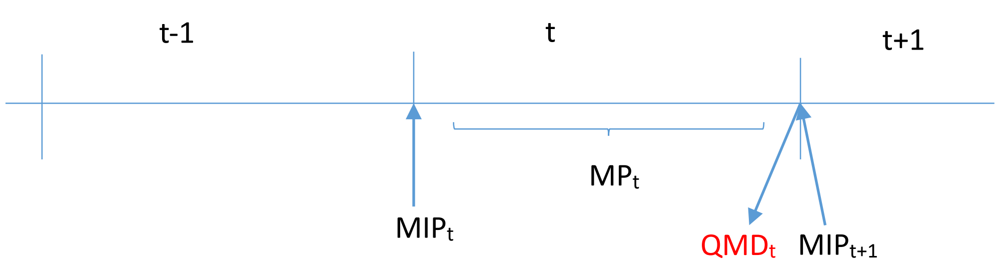

Figure 5. The schematic diagram of the products inventory balance equation at the manufacturing site.

For equation (16), the backlogged products at the manufacturing site are the demand of the distributor asks at the end of the period plus the backlogged products at the manufacturing site at the previous period minus the actual shipped product to the distribution center at the end of the period. There is also the inventory of parts at the manufacturing site if the quantities of refurbished parts from the refurbishing center are beyond the order quantities at the manufacturing site.

$$MI_{i,t+1} = MI_{i,t} + MO_{i,t} + RP_{i,t} - a_i * MP_t \quad (17)$$

The inventory of the parts at the beginning of the next period is the inventory of the parts at the beginning of the period plus ordering parts from external supplier at the end of the period plus the refurbished parts shipped from the refurbishing center at the end of the period minus the parts of product orders during the period. Figure 6 demonstrates the schematic diagram of the components' inventory balance equation at the manufacturing site, Eq. (17).

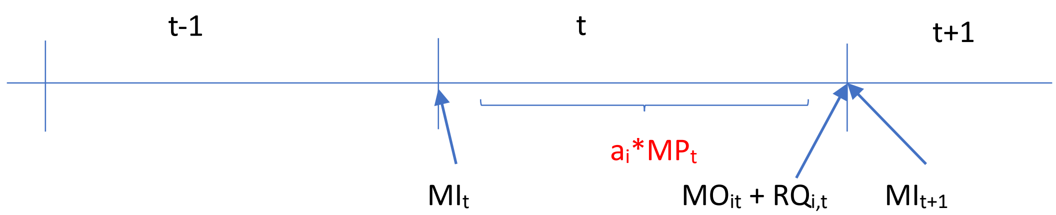

Figure 6. The schematic diagram of the components inventory balance equation at the manufacturing site.

The Eq.(18) shows if there is an oversupply at the distribution center. Besides, there is a backlog at the distribution center if the customer demand cannot be satisfied.

$$DI_{t+1} = DI_t + QMD_t + CU_t - QDC_t \quad (18)$$

$$STDC_t = STMD_{t-1} + X_t - QDC_t \quad (19)$$

The inventory of the product at the beginning of the period is the previous inventory of the product at the beginning of the period plus the previous delivered product from the manufacturing site at the beginning of the period plus the previous reused product shipped from the collection center at the end of the period minus the actual selling at the end of the period. Figure 7 demonstrates the schematic diagram of the products' inventory balance equation at the distribution center, Eq. (18).

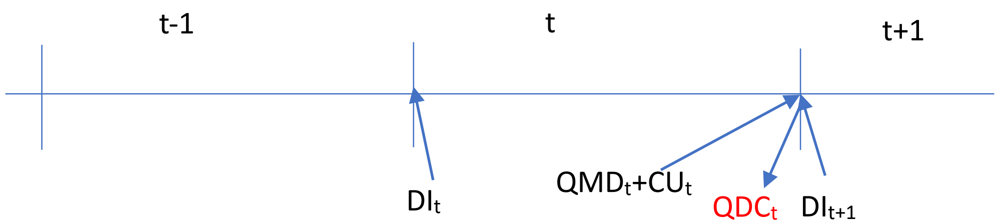

Figure 7. The schematic diagram of the products inventory balance equation at the distribution center.

In equation (19), the backlogged products at the distribution center are the backlogged products at the distribution center at the previous end of the period plus the orders of the customer during the period minus the actual shipped product to customers at the end of the period. Eq. (20) and Eq.(21) ensures the inventory balance of products and parts store in the disassembly center and the refurbishing center.

$$AI_{t+1} = AI_t + CA_t - AP_t - APS_t \qquad (20)$$

$$RI_{i,t+1} = RI_{i,t} + AR_{i,t} - RP_{i,t} - RPS_{i,t} \qquad (21)$$

When the rate of disassembly is lower than the rate of shipping from the collection center, it will become inventory to be saved at the disassembly center. In Eq. (20), the products' inventory at the disassembly center at the beginning of the period is the previous product inventory of the disassembly center at the beginning of the period plus the products shipped from the collection center at the end of the period minus the disassembled products at the disassembly center during the period and minus the disposal products. Figure 8 demonstrates the schematic diagram of the products inventory balance equation at the disassembly center, Eq. (20).

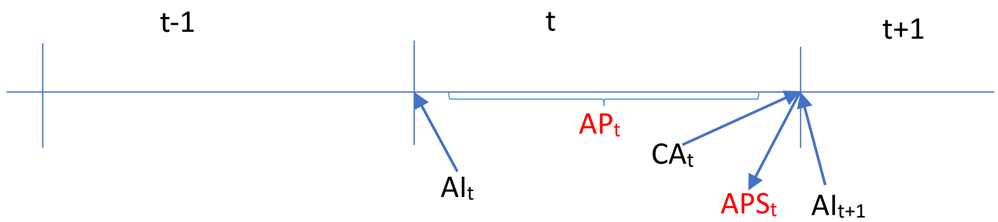

Figure 8. The schematic diagram of the products inventory balance equation at the disassembly center.

Similarly, the parts obtained from the disassembly center will be refurbished at the refurbishing center and then shipped to the manufacturing site at the end of the period. If the parts shipped from the disassembly center are more than the maximum operation rate at the refurbishing center, there are inventories at the refurbishing center at the beginning of the period. In Eq. (21), the parts inventory at the refurbishing center at the beginning of the period is the previous parts inventory at the beginning of the period plus the previous parts shipped from the disassembly center at the end of the period minus the previous parts refurbished at the refurbishing center during the period minus the disposal parts. Figure 9 demonstrates the schematic diagram of the products inventory balance equation at the distribution center, Eq. (21).

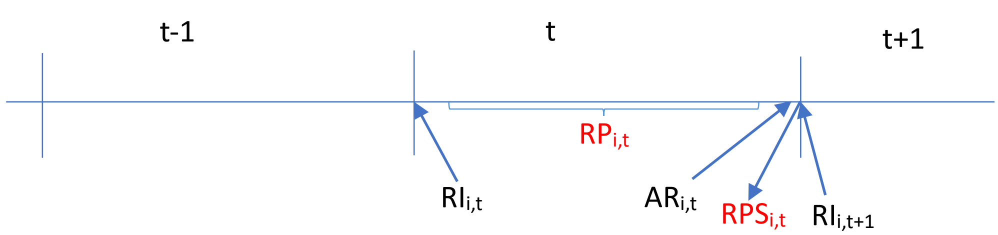

Figure 9. The schematic diagram of the products inventory balance equation at the refurbishing center.

4.8.4 Flow balance constraint

In constraint (22), the returned product, whose quantities are based on the actual selling quantities to customers, returned from the customer market, would be shipped to the collection center by the customer during the period.

$$CR_t = b * QDC_{t-1} \quad (22)$$

The quantities of the returned product during the period is a constant percentage of return rate of the product times the actual shipped quantities from the distribution center to the customer at the beginning of the previous period. Therefore, after the product is tested at the collection center, the product that follows the reused rate of the returned product could be reused and would be shipped to the distribution center at the end of the period shown in constraint (23); the remaining product in constraint (24) would be shipped to the disassembly center at the same time. There is a lead time for the collection center to classify the returned product.

$$CU_t = \mathrm{d} * CR_{t-1} \quad (23)$$

$$CA_t = (1 - \mathrm{d}) * CR_{t-1} \quad (24)$$

The quantities of reused product during the period are also a constant percentage of the reuse rate of the product times the returned product during the previous period. On the other hand, the product that cannot be reused equals to remaining rate of the product times the returned product during the previous period.

Eq. (25) shows that there is a constant disassembly percentage at the disassembly center. The returned product shipped from the collection center at the end of the period will be disassembled and became usable at a constant rate at the same period, the remaining products that are too late to be disassembled will be stored at the inventory of the disassembly center, and other products that cannot be disassembled will be disposed of, which is shown in Eq. (26).

$$AP_{t+1} = s * CA_t \quad (25)$$

$$APS_{t+1} = (1 - s) * CA_t \quad (26)$$

The quantities of the successfully disassembled products during the next period should be less than the constant rate of disassembling times the returned product shipped from the collection center at the end of the period.

Also, there is a constant refurbish rate at the refurbishing center. The disassembled products shipped from the disassembly center at the end of the period will be examined to see whether they can be refurbished at the constant percentage. Moreover, the other disassembled components that are not able to be refurbished will be disposed of.

$$RP_{i,t+1} = f_i * AR_{i,t} \qquad (27)$$

$$RPS_{i,t+1} = (1 - f_i) * AR_{i,t} \qquad (28)$$

The quantities of the successfully refurbished parts during the next period should equals to the constant rate of refurbishing times the disassembled parts shipped from the disassembly center at the end of the period.

4.8.5 Ordering constraint

Constraint (29) defines ordering quantities of parts from the external supplier determined after we know the quantities of refurbished parts that would be shipped to manufacturing site.

$$MO_{i,t} \geq a_i * MP_t - RP_{i,t-1} - MI_{i,t} \qquad (29)$$

The ordering parts from external supplier are the quantities of the parts at the end of the period, which are the quantities they predict to produce during the period minus the parts shipped from the refurbishing center to the manufacturing site at the end of the previous period minus the parts inventory at the beginning of the period. However, if the refurbished parts and the part inventories at the manufacturing site can satisfy the components that need to be produced, the manufacturer does not order the components for the external supplier.

There are two product sources for the distributor including the reused products that would be shipped to the distribution center (CU_t) and ordering quantities of the product requested for the manufacturer from the distribution center (OQ_t) that could be written as Eq.(30)

$$OQ_t \geq DU_{t+1} - DU_t + X_t - CU_t \qquad (30)$$

The order quantities for the manufacturing site from the distribution center should be bigger than the difference of the order-up-to level in the distribution center in the next and the current period plus the orders of the customer and minus the reused products shipped at the end of the period.

4.8.6 Production quantity constraint

Constraint (31) ensures that the volume of production, which is also the orders of the manufacturing site, can satisfy order-up-to-level. The parts at the manufacturing site would be made into the products during the period.

$$MP_t \geq MU_{t+1} - MU_t + OQ_t \qquad (31)$$

The quantities of product made during the period are based on the difference between the expected order-up-to (OUT) level and current OUT level of product inventory during the period plus the orders placed by the distributor at the end of the period.

4.8.7 Shipment constraint

Constraint (32) ensures that shipped products to the distribution center are less than the manufacturing supplier provides.

$$QMD_t \leq MIP_t + MP_t - STMD_t \qquad (32)$$

The actual shipped product for the distribution center is less than or equal to the product inventory at the manufacturing site at the beginning of the previous period plus the ordering quantities at the manufacturing site during the period minus the backlogged product at the end of the last period. Constraint (33) ensures that the shipped products to the customer are less than or equal to the distributor supplies.

$$QDC_t \leq DI_t + QMD_t + CU_t - STDC_t \qquad (33)$$

The actual selling for the customer is less than or equal to the inventory at the distribution center at the beginning of the previous period plus the actual delivered products from the manufacturing site to the distribution center plus the reused product from the collection center at the end of the period minus the backlogged product at the distribution center at the end of period.

4.8.8 Capacity constraint

Constraint (34) to (37) provide the maximum limit rate on production, distribution, assembly, and refurbishing, respectively.

$$MP_t \leq MC \qquad (34)$$

$$QDC_t \leq DC \qquad (35)$$

$$\mathrm{A}P_t \leq AC \qquad (36)$$

$$RP_{i,t} \leq RC \qquad (37)$$

4.8.9 Nonnegative restriction for decision variables

The following constraints related to the variables are positive numbers.

$$MO_{i,t}, MP_t, MU_t, QMD_t, QDC_t, STDC_t, STMD_t, MIP_t, DI_t, DU_t, MI_{i,t}, \quad (38)$$

$$CR_t, CU_t, CA_t, AP_t, AR_{i,t}, RP_{i,t}, AI_t, RI_t, OQ_t, APS_t, ARS_{i,t} \geq 0$$

4.9 Bullwhip index

According to a definition in the literature, the bullwhip index of the retailer is the ratio of the variance of orders placed by the retailer to the variance of customer demand seen by the retailer (Dejonckheere et.al. 2003; Simchi-Levi, et al. 2008; Agrawal et al. 2009; Costantino et.al. 2015).

Similarly, the bullwhip index of the distribution center in our research is the ratio of the variance of orders placed by the distributor to the variance of the order placed by the customer:

$$\text{BW index of DC} = \frac{var(OQ)}{var(X)} \qquad (39)$$

Var(OQ) is the variance of orders placed by the distribution center and *Var(X)* is the order placed by the customer. It is worth mentioning that we consider the bullwhip effect in the closed-loop supply chain in this research so we consider ordering quantities for the manufacturing site that exclude the product from the collection center to measure the bullwhip index. The ordering quantity from the distributor OQ_t illustrated in Eq. (27) in the previous section and customer demands X_t are random numbers following normal distribution whose variance is 100. Moreover, we calculate the bullwhip index generated at the manufacturing site. In the same way, the bullwhip index of the manufacturing site in our research is the ratio of the variance of ordering quantities requested by the manufacturer at the manufacturing site to the variance of orders placed by the customer:

$$\text{BW index of mfg} = \frac{var(MP)}{var(X)} \qquad (40)$$

Where *Var(MP)* is the variance of ordering quantity at the manufacturing site.

To ensure the stability of the model, we ran it 1000 times and selected the result in period 5 to period 994, a total of 990 periods to analyze.

4.10 The best of the best test

In our model, we chose the best smoothing parameter by comparing the total cost with or without information sharing separately in the closed-loop supply chain. Then, we compare the bullwhip index in the model with information sharing and the model without information sharing. The schematic diagram of the best of the best method in this research shows the following.

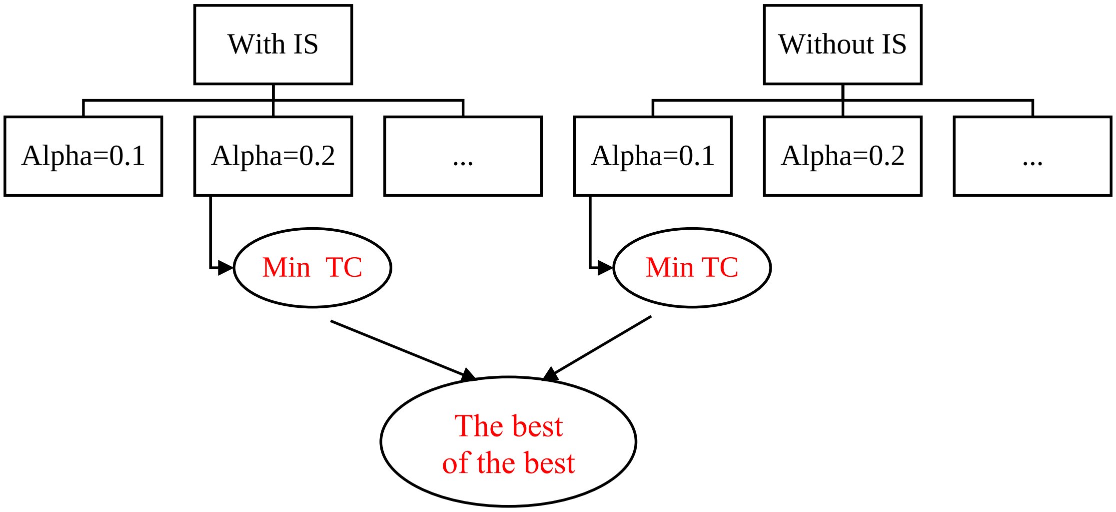

Figure 10. Schematic diagram of the best of the best method.

We chose the best performance of minimizing total cost by linear programming with a good forecasting parameter in the exponential smoothing forecasting with trend method. The objective of the model is minimizing the total cost, which consisted of production setup cost, ordering cost, inventory holding cost, and shortage cost. Now, we obtained the best parameter (Alpha value) within the model with and without information sharing. Then, we compared the bullwhip index of the best result of minimizing the total cost. Briefly, in this research, we compared the bullwhip effect based on the bullwhip index of the case with IS and without IS. Moreover, the bullwhip index was chosen based on the Alpha value. We chose the best result of minimizing total cost among different Alpha values and compared the result of BWE with and without IS.

5. Results

5.1 Determination of the smoothing factor for minimizing total cost of the SC

One of the objectives of this research is checking if the BWE is reduced by information sharing when minimizing the total cost of the supply chain; we evaluated the performance via the best of the best test in our research. To obtain the best of the best test in our research, we determine the smoothing parameter of the exponential smoothing forecasting method of the model by minimizing the total cost. In Section 5.1, we determine the best result of minimizing total cost with the model with and without information sharing.

5.1.1 Without information sharing

Because a smoothing parameter affects the accuracy of the forecasting, the first step for the best of the best method is comparing different parameter values and selecting a good parameter value for minimizing the total cost. The performance of the total cost includes production cost, shipping cost, ordering cost, inventory cost, and shortage cost. The shipping cost is $5 per unit. Inventory cost is $1 per unit. Production cost at the manufacturing site is $10 per unit. The shortage cost if the demand cannot be satisfied at the manufacturing site and the distribution center is $80 per unit. Eventually, we assumed that the ordering cost if we do not have any inventory or the components shipped from the refurbishing center to produce are $100 per unit to use the refurbished components as much as possible.

The two smoothing parameters in the exponential smoothing forecasting with the trend, respectively, are the smoothing constant for the level of the series of the forecasting model and the smoothing constant for the trend of the series of the forecasting model. Chen et al. (2000) indicated that the increase in variability that results in BWE does not depend on the magnitude of the linear trend. We determined to compare Alpha values and gave the smoothing parameter for the trend a constant value, 0.3. Through optimizing the linear programming in our research, we listed the performance of the minimum total cost in the model 10 times in different smoothing parameters, Alpha value, in Table 1.

Table 1. Performance of the models in different parameter without information sharing. (Beta = 0.3)

Total cost				
Alpha=0.1	Alpha=0.2	Alpha=0.3	Alpha=0.4	Alpha=0.5
$287,815,100	$288,069,300	$288,402,200	$288,567,500	$288,914,500
$287,665,200	$287,694,500	$287,987,300	$288,548,100	$289,041,100
$287,960,600	$288,185,600	$288,096,000	$288,818,800	$289,287,600
$287,789,500	$287,853,900	$288,174,600	$288,851,100	$289,135,700
$287,770,600	$287,889,800	$288,310,200	$288,925,100	$289,048,000
$288,045,500	$288,176,100	$287,905,500	$288,551,400	$288,760,900
$288,184,100	$288,011,400	$288,336,800	$288,911,400	$289,146,100
$287,733,100	$288,136,800	$287,901,700	$288,833,600	$288,965,700
$288,076,200	$287,958,400	$288,412,600	$289,021,600	$288,920,900
$287,936,000	$287,933,200	$288,017,500	$288,755,900	$288,840,700
Average				
$287,897,590	$287,990,900	$288,154,440	$288,778,450	$289,017,390

In Table 1, we know the lower total cost is $287,897,590 with the Alpha value equals 0.1. That is to say, the best result of minimizing the total cost of the model without information sharing is that Alpha equals 0.1. Despite obtaining the best result of the model without IS, we can see the different total costs between different Alpha values are not significant.

Due to the fact that the best performance between different Alpha values is not obvious, we analyzed the cost of different categories and observed which cost type is the most influential by Alpha value. We compared the difference of categorized costs that are production cost, shipping cost, ordering cost, inventory cost, and shortage cost and the costs between the larger Alpha value minus the smaller Alpha value, and then we divided by their categorized cost. Table 2 shows the costs of different types when all of the costs are equal to 1 dollar.

Table 2. Categorized cost in the difference between the smoothing parameter.

Categorized cost	Alpha=0.1	Alpha=0.2	Alpha=0.3	Alpha=0.4	Alpha=0.5
Shipping cost ($1/unit)	$3,278,918	$3,280,170	$3,279,106	$3,281,300	$3,276,464
Production cost ($1/unit)	$409,433	$409,610	$409,534	$409,963	$409,402
Inventory cost ($1/unit)	$2,899,514	$2,933,558	$3,000,476	$3,077,325	$3,150,264
Ordering cost ($1/unit)	$2,642,397	$2,643,740	$2,643,358	$2,646,822	$2,643,505
Shortage cost ($1/unit)	$6,700	$7,646	$8,636	$9,036	$10,593

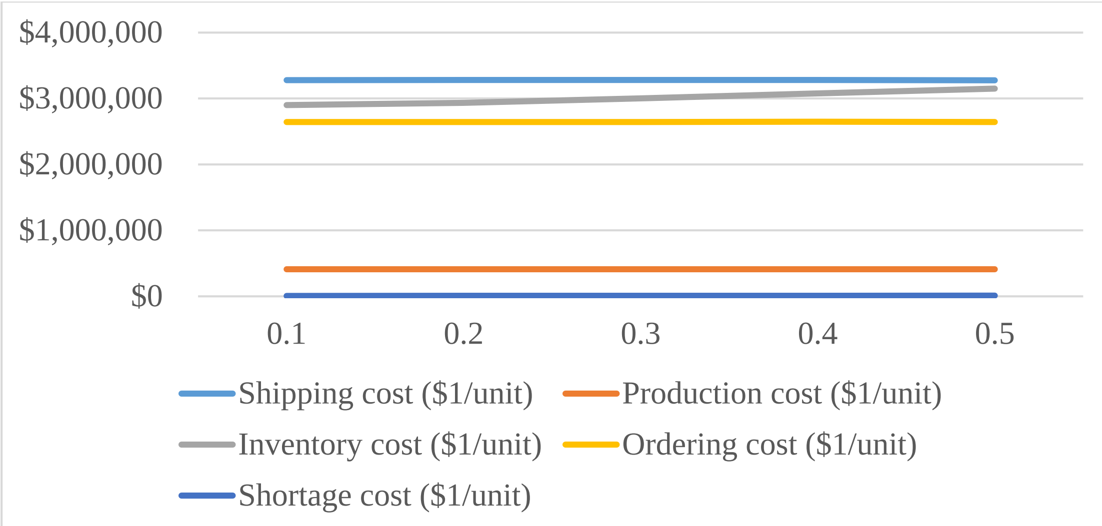

Figure 11. Categorized cost of the difference of the smoothing parameters.

Table 2 and Figure 11 show that the most difference with the different smoothing parameters is the inventory cost. We could not see a significant difference in Table 1 because the inventory cost is only 1 dollar in our assumption. However, Figure11 shows the inventory cost increase as the Alpha value becomes larger. Also, the inventory cost is changed larger than others when all of the categorized cost equals 1 dollar in the model. That is to say, the total cost will greatly differ in different smoothing parameters if the inventory cost becomes larger.

Based on minimizing the total cost in Table 1, we know the result of the smoothing parameter $\alpha=0.1$ is the best result of minimizing the total cost of the model without information sharing. Next, we consider the smoothing parameter of the model with information sharing when minimizing the total cost.

5.1.2 With information sharing

When there is information sharing within the forward supply chain, the manufacturer can forecast the ordering quantity at the manufacturing site by the information of the orders of the customer instead of forecasting through the orders from the distribution center. The manufacturer obtains the information of the orders of the customer so he will produce the product by forecasting the demand through the information of the orders of the customer. Hence, we rewrite a new forecast equation at the manufacturing site. Substitute the orders from the distribution center (OQ_t) to the orders of the customer (X_t). The equation can be found in Eq. (12).

$$MF_t = \alpha * X_{t-1} + (1-\alpha) * ML_{t-1} + \beta * (ML_t - ML_{t-1}) + (1-\beta) * MT_{t-1} \quad (41)$$

Moreover, the manufacturer obtains not only the information of the orders of the customer but also the information of the returned product from the collection center. We can reduce the ordering quantities at the manufacturing site since we know some returned products would be shipped to the distribution center and satisfy the orders of the customer.

$$MP_t \geq MU_{t+1} - MU_t + X_t - CU_t \qquad (42)$$

Table 3. Performance of the models in different parameters with information sharing. (Beta=0.3)

Total cost				
Alpha=0.1	Alpha=0.2	Alpha=0.3	Alpha=0.4	Alpha=0.5
$287,576,900	$287,884,600	$287,772,200	$288,092,800	$288,079,200
$287,794,700	$288,114,000	$287,739,900	$288,112,500	$287,850,400
$287,753,600	$287,815,200	$288,126,400	$287,959,800	$288,094,500
$287,588,400	$287,875,900	$287,936,100	$288,069,300	$288,295,200
$287,928,600	$287,659,100	$287,999,200	$287,858,900	$288,168,900
$287,708,700	$287,622,700	$288,570,700	$288,033,200	$288,176,200
$287,612,300	$288,014,000	$287,745,000	$288,111,500	$288,028,100
$288,055,000	$287,663,700	$287,869,500	$288,002,000	$287,979,300
$288,201,700	$287,818,800	$288,161,100	$288,312,000	$288,298,900
$287,860,000	$287,902,600	$287,749,600	$287,851,400	$287,767,000
Average				
$287,807,990	$287,837,060	$287,966,970	$288,040,340	$288,083,740

Table 3 illustrates the result of the bullwhip index of the model in different smoothing parameters with information sharing. It demonstrates that the best performance of the bullwhip index is the smoothing parameter α=0.1 of the model with information sharing. Figure 12 illustrates the average of the total cost with a different Alpha value in the closed-loop supply chain with and without information sharing.

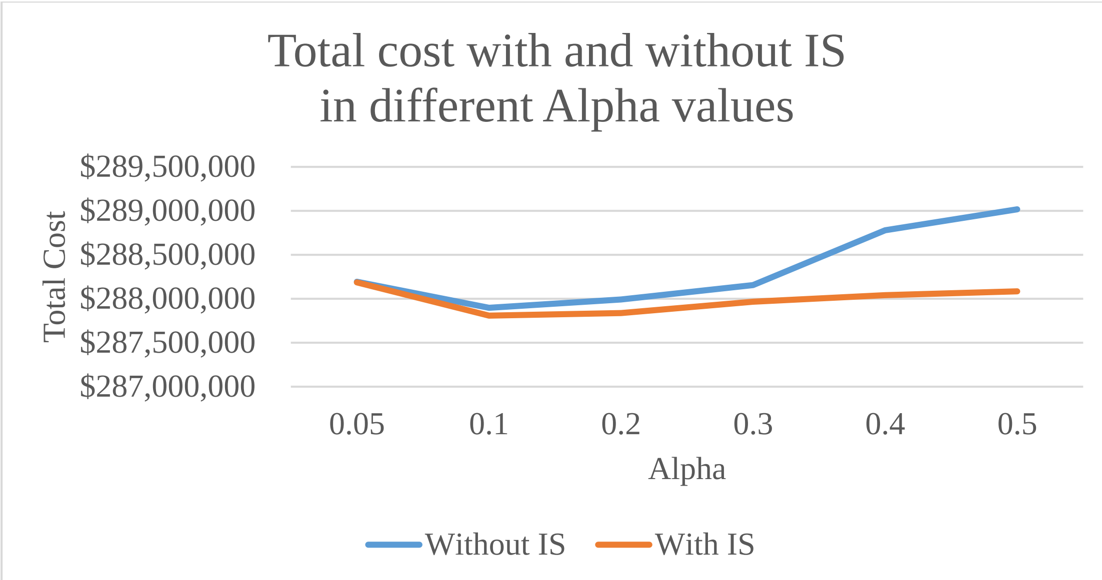

Figure 12. Total cost with and without IS in different Alpha values.

Based on the result of Table 1, Table 3, and Figure 12, the smoothing parameter, α=0.1, is chosen for a good smoothing parameter for minimizing the total cost with the model with and without information sharing. In this figure, we can also observe the average total cost when the Alpha value=0.05 is larger than Alpha value=0.1. This figure forms a convex function. When the Alpha value is larger than 0.1, the smaller the Alpha values, the smaller the total cost. In addition, the total cost with the model with IS is smaller than the model without IS.

5.2 Comparison of the BW index with and without information sharing

In Section 5.1, we know the BWEs of the CLSCs with and without IS for the chosen Alpha value (Alpha=0.1) from the above section are evaluated in this section. In this section, we check if the BW index of the model with the Alpha value equals 1 is decreased by IS in the model. The results are shown in the first and second columns of Table 4 (without IS) and Table 5 (with IS) when Alpha =0.1. From the columns we notice that the bullwhip index of the manufacturing site is larger than the bullwhip index of the distribution center. The bullwhip index at the distribution center would not be different unless of the minimal error because of the random customer demand. We also notice that the bullwhip index at the manufacturing site is decreased by information sharing.

Table 4. The bullwhip index in different smoothing parameters without information sharing.

Bullwhip index									
α=0.1,β=0.3		*α=0.2,β=0.3*		*α=0.3,β=0.3*		*α=0.4,β=0.3*		*α=0.5,β=0.3*	
BW index (DC)	BW index (MFG)	BW index (DC)	BW index (MFG)	BW index (DC)	BW index (MFG)	BW index (DC)	BW index (MFG)	BW index (DC)	BW index (MFG)
1.332	1.745	1.681	2.871	2.029	4.408	2.489	6.824	3.087	10.687
1.307	1.715	1.634	2.781	2.047	4.456	2.491	6.827	2.925	9.961
1.306	1.713	1.648	2.797	2.052	4.461	2.433	6.611	2.99	10.354
1.314	1.719	1.627	2.76	1.982	4.251	2.458	6.758	2.994	10.33
1.325	1.74	1.644	2.792	2.001	4.323	2.482	6.867	2.962	10.178
1.311	1.721	1.685	2.875	2.033	4.375	2.481	6.841	3.014	10.452
1.307	1.715	1.631	2.774	2.02	4.392	2.493	6.822	2.973	10.094
1.331	1.741	1.693	2.891	2.057	4.477	2.509	6.863	3.042	10.54
1.336	1.757	1.644	2.787	2.083	4.531	2.498	6.851	2.989	10.192
1.353	1.775	1.642	2.781	2.043	4.448	2.419	6.58	3.027	10.602
Average									
1.322	1.734	1.653	2.811	2.035	4.412	2.475	6.784	2.996	10.323

Table 5. The bullwhip index in different smoothing parameters with information sharing.

Bullwhip index									
α=0.1,β=0.3		*α=0.2,β=0.3*		*α=0.3,β=0.3*		*α=0.4,β=0.3*		*α=0.5,β=0.3*	
BW index (DC)	BW index (MFG)	BW index (DC)	BW index (MFG)	BW index (DC)	BW index (MFG)	BW index (DC)	BW index (MFG)	BW index (DC)	BW index (MFG)
1.306	1.336	1.655	1.725	2.067	2.19	2.489	2.675	3.023	3.287
1.32	1.35	1.639	1.708	2.047	2.168	2.474	2.657	2.933	3.189
1.307	1.337	1.629	1.698	2.045	2.166	2.475	2.659	2.899	3.15
1.304	1.335	1.644	1.713	2.033	2.154	2.499	2.683	3.059	3.327
1.301	1.331	1.648	1.718	2.034	2.156	2.491	2.674	2.94	3.195
1.317	1.347	1.677	1.748	2.063	2.186	2.461	2.644	3.037	3.301
1.329	1.359	1.663	1.733	2.026	2.146	2.467	2.647	2.996	3.259
1.321	1.351	1.61	1.679	2.052	2.174	2.465	2.645	2.95	3.206
1.311	1.341	1.641	1.711	2	2.118	2.456	2.637	3.053	3.319
1.313	1.343	1.606	1.673	2.073	2.195	2.437	2.615	3.113	3.386
Average									
1.313	1.343	1.641	1.711	2.044	2.165	2.471	2.654	2.999	3.260

The above facts prove that the definition of the fluctuation in demand in the downstream results in a drastically amplified fluctuation in demand in the upstream is also applicable in the closed-loop supply chain. We observe that there is a little error at the distribution center because of the random demand generation. Furthermore, the model with information sharing can decrease the bullwhip index. Based on the performance shown in Table 4 and 5, the model with Alpha=0.1 with information sharing can reduce the BW index in the closed-loop supply chain in this research. Moreover, Figure 13 clearly shows the decrease of the bullwhip index of the manufacturing site by information sharing.

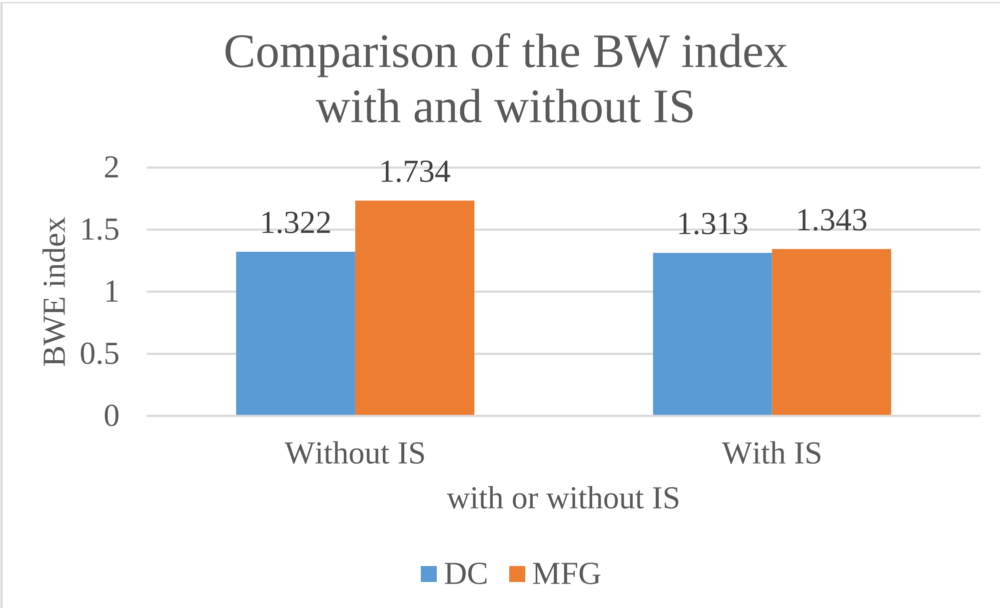

Figure 13. Comparison of the BW index with and without IS

Figure 13 demonstrates the bullwhip indexes at the distribution center and the manufacturing site. The BW index at the distribution center with the model is 1.322 and the BW index of the manufacturing site is 1.734 with the model without IS; the BW index of the distribution center is 1.313, and the BW index at the manufacturing site is 1.343 with the model with IS. According to Figure 13, the BW index of the manufacturing site decreases 23% through information sharing.

This result verifies that the bullwhip index of the model with information sharing can be decreased in the closed-loop supply chain. The percentage of reducing also emphasizes the importance of information sharing in the closed-loop supply chain. The best of the best test shows that we can utilize the smaller Alpha value when we forecast by the exponential smoothing forecast method with trend to reduce the total cost. Furthermore, information sharing provides an opportunity to decrease the bullwhip effect at the manufacturing site. If the manufacturer predicts the ordering quantities at the manufacturing site through the information about the orders of the customer and the returned products from the collection center, the bullwhip index will be decreased.

5.3 Change of the supply chain costs by information sharing

One of the objectives of the research is how the various types of costs are changed with information sharing. As we discussed in Section 5.1.1, the inventory cost is a vital reason that influences the total cost in different smoothing parameter values. Now, we are interested in knowing which type of cost is the most influential between the model with and without information sharing. Therefore, we compared the categorized cost in the model with IS and without IS for 5 times with Alpha value is 0.1. We calculated the categorized cost through the difference between the model with IS and without IS, then divided by their cost to compare them fairly.

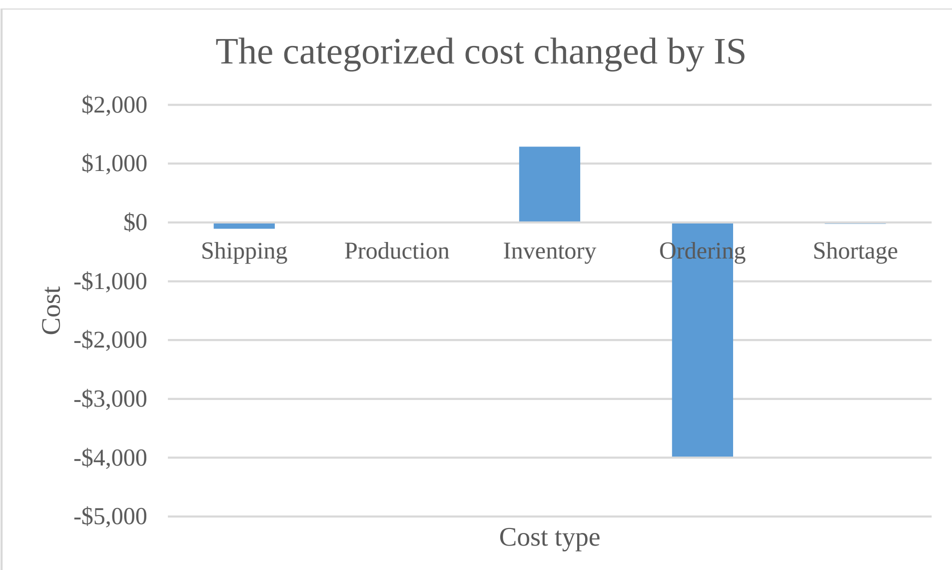

Figure 14. The difference of categorized cost between with and without IS.

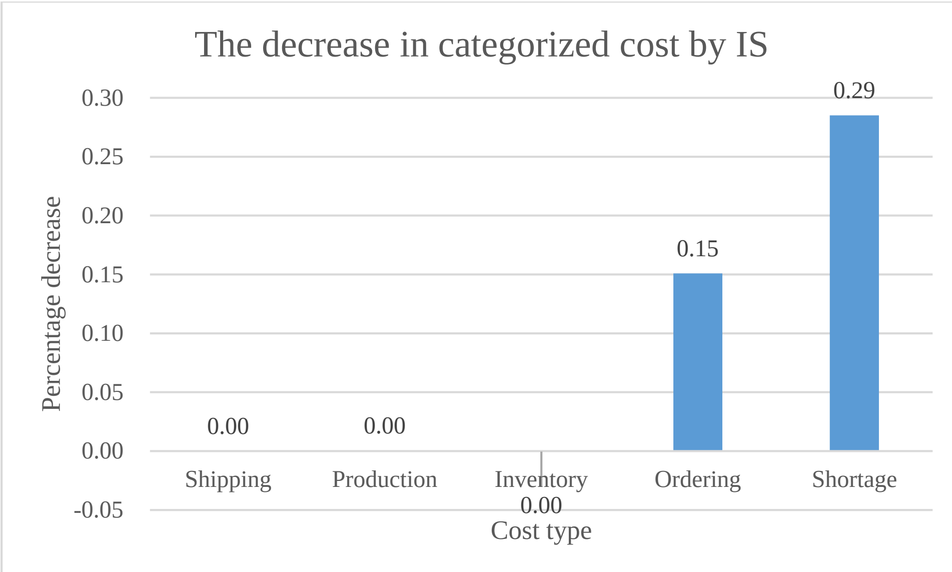

Figure 15. The decrease in categorized cost by information sharing.

Figure 14 and 15 show that the ordering cost is reduced 15% and the shortage cost is reduced 29% when there is information sharing in the model. To be more specific, the most influential cost for the total cost is the ordering cost and the shortage cost when we consider information sharing. Once the manufacturer knows the information about the orders of the customer and the returned product quantities, he will not prepare so many components that are needed to place the orders from the external supplier. Moreover, when there is information sharing in the supply chain, the shortage will be reduced a lot and the shortage costs will be saved. Therefore, the ordering cost and the shortage cost will be reduced a lot, such as illustrated in Figure 15. In addition, the inventory cost did not decrease because of information sharing, but increased.

As we observed in the inventory cost, we noticed that the most increased cost with the model with information sharing is the component inventory cost at the manufacturing site. Information sharing helps the manufacturer to produce fewer products to reduce the product inventory at the manufacturing site; however, he cannot control the components shipped from the refurbishing center. This leads to the component inventory costs increase.

5.4 The total cost and BW index of the model with and without IS in different Alpha values

Figure 10, which was shown in Section 5.1.2, shows that the larger Alpha value in the forecasting can increase the total cost. Moreover, the total cost can be reduced by information sharing not only when the smoothing parameters value is 0.1, but also other values of the smoothing parameters. We know the total cost will decrease with a smaller Alpha value; however, we cannot ensure if this is an advantage for the company if the BW index increases at the mean time. To ensure the necessity of total cost and bullwhip effect that can be saved by Alpha value and information sharing, we checked if the BW index at the manufacturing site can be decreased by information sharing with different Alpha values and how many degrees of the BW index were reduced.

According to Figure 16 and 17, we found that the bullwhip index of the distribution center and the manufacturing site would be decreased through the smaller parameter value. This result indirectly confirms the viewpoint of Ravinder (2013) that the smaller smoothing parameter can decrease the forecast error. The decreasing forecast error can provide the decision-makers to precisely determine the orders and reduces the BWE. Furthermore, we verified that the same situation will happen in either the model with information sharing or without information sharing, and that the bullwhip index will decrease by decreasing the value of the smoothing parameter.

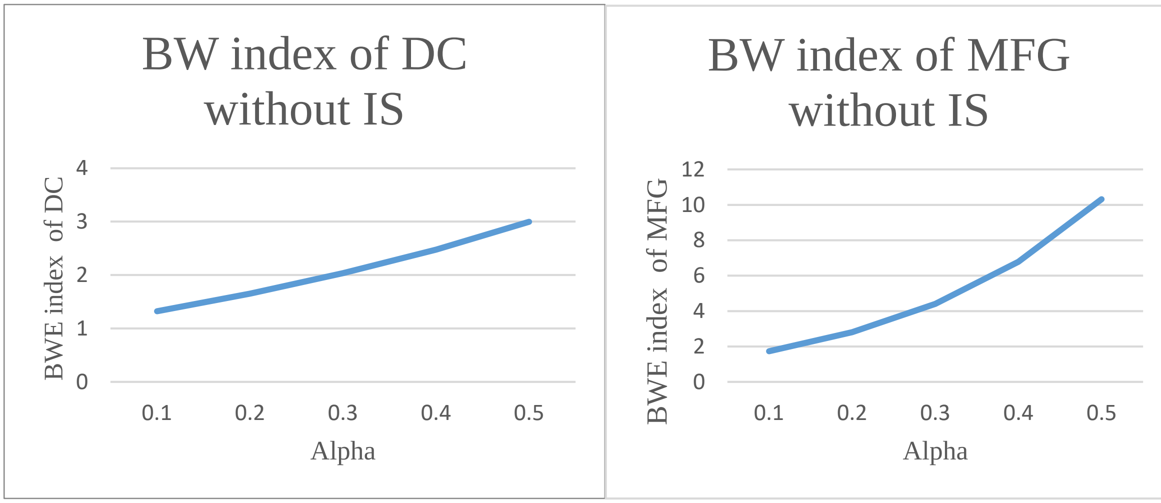

Figure 16. BW index of DC and MFG without IS when Beta is 0.3.

Figure 16 presents the increasing trend of the BW index at the manufacturing site and the distribution center as the Alpha value gets bigger with the model without information sharing.

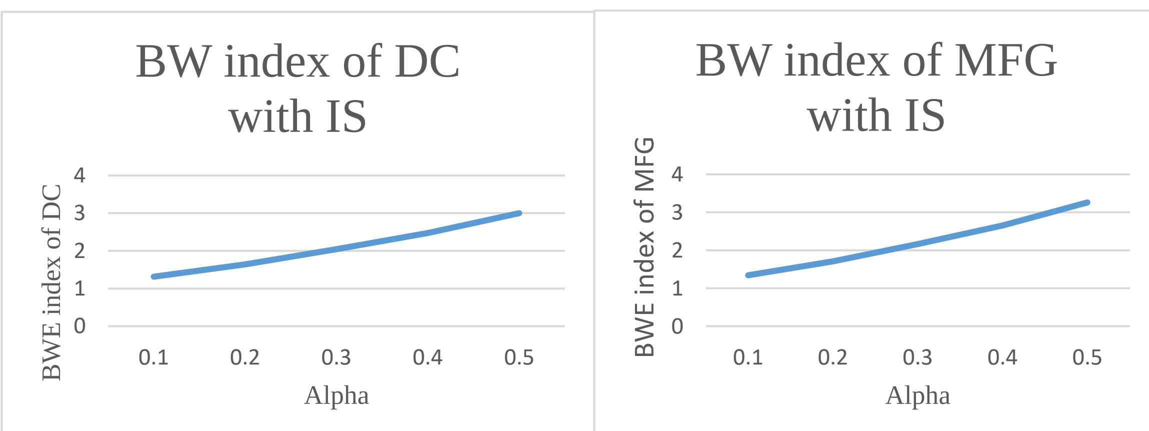

Figure 17. BW index of DC and MFG with IS when Beta is 0.3.

Besides, Figure 17 also illustrates that the trend of the BW index also increases at both of two echelons with information sharing. Furthermore, compared with Figure 16, we also observe that the phenomenon of the increasing tread of the BW index with the model with information sharing at the manufacturing site is much less than it is without information sharing. The result is the same as the decrease of the BW index with Alpha is 0.1, which we showed in Section 4.3.

Figure 18 illustrates the trend of the BW index at the manufacturing site with Alpha value larger than 0.1 with the model with and without IS, and Figure 19 displays the degree of the BW index decreased by information sharing at the manufacturing site. The larger the smoothing parameter value, the more the BW index can be decreased by information sharing at the manufacturing site for either the model with Alpha value larger than 0.1 with IS or without IS. As the figure shows, when the Alpha value equals 0.5, the degree of the difference even reaches 68%. The larger the Alpha value, the more the BW index decreases by information sharing at the manufacturing site.

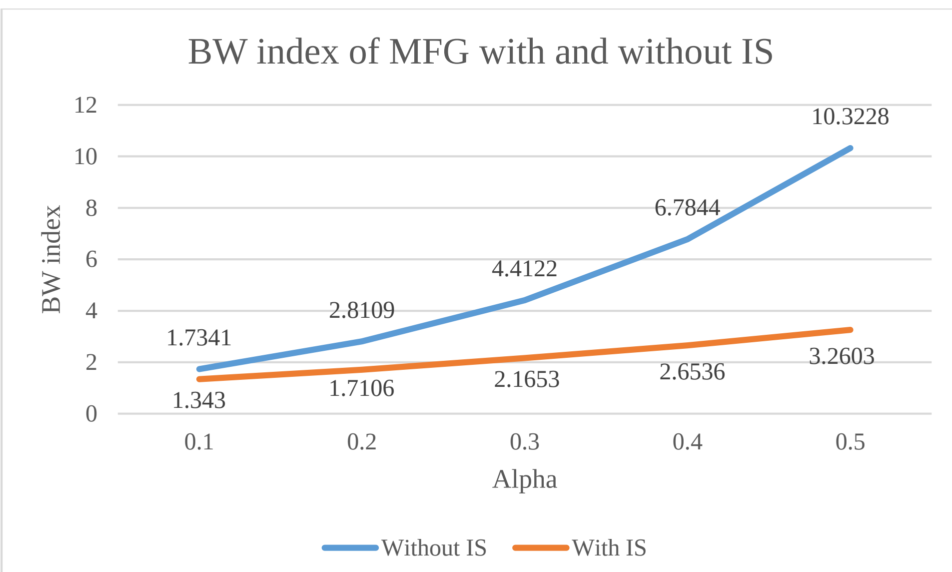

Figure 18. The BW index of MFG with and without IS.

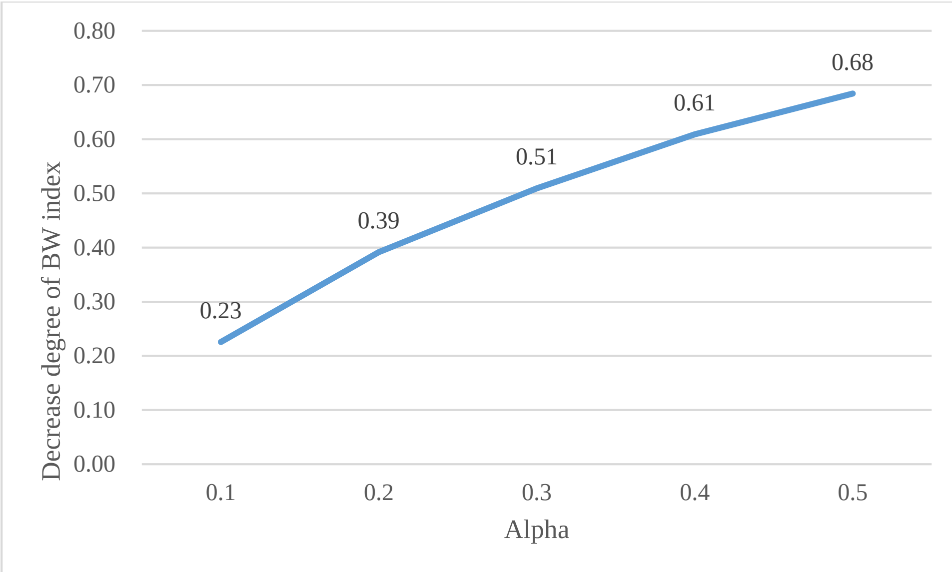

Figure 19. The degree of the BW index decrease of IS at MFG.

5.5 The BW index of the model with and without IS in different lead times

Lead time is an important factor in resulting in the BWE. Hence, we compare the BW index at the manufacturing site with and without IS in lead time=0.5, 1, and 1.5. Figure 20 illustrates the BW index at the manufacturing site without IS with lead time=0.5 is 1.34. The BW index at the manufacturing site with IS with lead time=0.5 is 1.18.

The result verifies that the BW index at the manufacturing site with lead time=0.5 is smaller than lead time=1. Furthermore, the BW index at the manufacturing site without IS with lead time=1.5 is 149.46, and the BW index at the manufacturing site with IS with lead time=1.5 is 145.49. Both the BW index at the manufacturing site with IS and without IS with lead time=1.5 is much larger than the BW index at the manufacturing site with lead time=0.5 and 1.

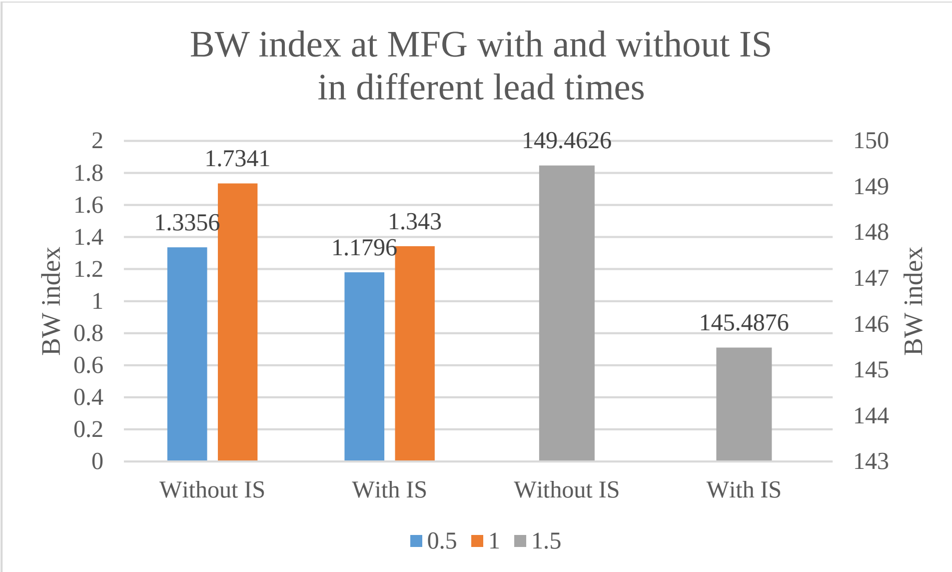

Figure 20. BW index at MFG with and without IS in different lead times.

6. Conclusion

In our research, we constructed an optimized model to study the CLSC and we also proposed a model to verify the BWE of IS. In Chapter 5, we selected the best result for minimizing the total cost, Alpha value=0.1. Then, we compared the bullwhip index of the model with and without IS. According to Section 5 we have the following observations.

- Alpha value equal to 0.1 is the best smoothing factor in the ES forecasting method.
- The BWE can be decreased by IS in the CLSC by 23% in the example case.
- The total cost is reduced by smaller smoothing parameters when the Alpha value ≥ 0.1
- Ordering costs can be reduced by 15% and the shortage cost can be reduced by 29 % with the model with information sharing.
- The inventory cost occupies a big part of the reason for the different total costs with different Alpha values.

As we ran the models 10 times, we obtained the best result of minimizing total cost and learned that information sharing is an essential strategy for reducing the bullwhip effect and the total cost in the closed-loop supply chain. According to the result, we can say that the bullwhip effect at the manufacturing site can be decreased via information sharing. This result also proves that information sharing is one of the solutions of the bullwhip effect mentioned in many works of literature and books (Tang and Naim, 2004; Simchi-Levi et al. 2008; Zanoni et al. 2013).

In addition, we observed either the model with information sharing or without information sharing, the total cost and the BW index can be decreased in the smaller Alpha value if the Alpha value larger than 0.1. To be more specific, the companies do not need to tradeoff between the total cost and the BW index while choosing the Alpha value. The smaller the Alpha value, the better performance of minimizing the total cost and reducing the BW index. Furthermore, the result also verifies that the longer the lead time, the larger the BW index occurred.

In our thesis, we provide a contribution to the following, building a model for a closed-loop supply chain with two different recovery pipelines, reusing and refurbishing. This model is considered the recovery that influences the bullwhip index in the closed-loop supply chain, ensuring that the BWE can be decreased by information sharing in the closed-loop supply chain and comparing the bullwhip index and the total cost of the model with and without IS among different smoothing parameters. Furthermore, we analyzed the cause of less reduction with different Alpha values. Inventory cost is too small to influence the total cost; however, the real-world cost will result in bigger different total costs and provide a stronger reason for choosing the best parameter. Also, the cause of the negative value of the bullwhip effect with information sharing is the increase of the component inventory at the manufacturing site.

There is a general solution for Beer Game, which is a game related to the BWE. That is to say, there is a general solution for the BWE in the traditional SC. In the future, people can develop a general solution for reducing the BWE in the CLSC. Moreover, people can consider other performance in the CLSC, such as social responsibility, consumption of resources and energy, and reducing emission or pollution.

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