Three-Level Closed-Loop Supply Chain Optimization Considering Self-Healing Packages

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Abstract

The challenge for maintaining a competitive and sustainable supply chains have been considered nowadays. To compete in the market, smart packaging and the utilization of closed-loop supply chains are widely studied. The self-healing packages and closed-loop supply chains are main components to help reduce carbon emissions. This study was about a three-level closed-loop supply chain considering self-healing packages of a single-supplier, single-manufacturer, and multiple retailers. The model was developed and optimized algebraically considering the overall cost minimization. Results of this study showed that the model could be used in real-life application. Total costs could be reduced by manipulating the different parameters such as the ordering costs, set-up costs, holding costs, purchase price and maintenance cost of self-healing packages, forward and reverse logistics transportation cost, and forward logistics variable transportation costs.

Keywords
Carbon Emission, Closed-loop Supply Chain, Optimization, Self-healing Packages, Transportation

1. Introduction

Maintaining a sustainable supply chain has been a challenge for most businesses nowadays since they must consider the merging of three dimensions: environmental, social, and economic aspects of a supply chain (Zadjafar and Gholamian, 2018). Knowing that some natural resources are finite such as petroleum, tin, and natural gas (Ruz, 2011), it is important to understand that the planet cannot sustain constant consumption of these fuels (Ruz, 2011). With this issue, retailers are already looking at the supply chain in a different manner. According to Deen (2017), instead of simply relying on the life cycle of a product before it is shipped to the consumers, most retailers are working to create a closed-loop supply chain that maximizes the efficiency of resources and creates less waste. Therefore, closed-loop supply chains are considered as a better set-up for industries. Closed-loop supply chain (CLSC) refers to the combination of forward logistics such as material sourcing, manufacturing, and distribution with reverse logistics pertaining to the storage and recycling of returned (used or unused) goods and/or pieces of products (Kumar N. and Kumar R., 2013). Moreover, according to Chen et al. (2020), any type of supply chain utilizing smart packaging could promote sustainability, quality, and safety of products.

Smart packaging was introduced to make packaging systems of food, appliances, and other products more efficient (Schaefer and Cheung, 2020). According to Schaefer and Cheung (2020), it is used to prolong a product's lifespan, improve the product, ensure customers' safety, and even monitor freshness. In smart packaging, self-healing packages are one of the main models (Mlalia et al., 2016). In the study of Mlalia et al. (2016), self-healing polymer materials have the capability to recuperate and fix the materials that have been damaged by returning to their structural features or original shape by using external stimuli. These external stimuli include configuring the material's viscosity and molecular mass which in return is easily repaired in the process of re-polymerization. Self-healing packages are utilized to reduce carbon emission (Sarkar et al., 2019).

One of the reasons why the environment is at risk for climate change is because of carbon emission (Environmental Protection Agency, 2018). Since the industrial revolution, the amount of carbon emission in the atmosphere increased (Lindsey, 2020). As a result, the Kyoto Protocol was implemented in Japan back in 1997 to reduce the carbon emissions in developed nations by at least 5%. In addition, Maamoun (2019) was able to explore how the Kyoto Protocol demonstrated success in lowering carbon emissions. The findings showed that the Protocol succeeded in reducing involved countries' emissions by about 7% below the projected emissions under the 'No-Kyoto' scenario.

This study focused on Sarkar et al. (2019) model, wherein self-healing packages of three-level supply chain following the single-setup-multi-delivery (SSMD) policy were considered. Their study opted for non-preemptive goal programming - a type of optimization process where goals are pre-set. It is worth noting that after optimizing numerous goals created for their model, it indicated that though the cost was minimized, it can be only applied for those same set of goals. In addition, Ong et al. (2020) dealt with a three-level supply chain considering carbon emission and transportation cost. The model was derived algebraically to determine the optimum result. The focus was reduction of costs that can be applied to any type of supply chain while lowering the carbon emission of industrial and transportation aspects. Hence, it was identified that these studies did not particularly focus on the optimization of the total cost of a three-level closed-loop supply chain considering self-healing packages wherein the goals were not pre-set.

1.1 Objectives
In this study, the proposed mathematical model was a framework for a three-level closed loop supply chain under the single set-up multiple delivery (SSMD) policy. Since the mathematical model used in the paper was an integration from Ong et al. (2020) and Sarkar et al. (2019), it will focus on optimizing the total cost of a three-level closed-loop supply chain that considers self-healing packages. The supply chain model is considered for single-supplier, single-manufacturer, and multi-retailer. Finally, the study will use Maple Software to perform sensitivity analysis to determine the optimality of the findings.

The results of this study would be useful for multiple sectors of a three-level closed-loop supply chain (CLSC) largely because it offers a general model for the overall expense of the system. In addition, this would be beneficial to the environment as it is inclined to determine which party of the supply chain has struggled to monitor and minimize the carbon emissions under the guidelines of the Kyoto Protocol. Lastly, it will be helpful to companies since they can decrease their expenses, which in turn will increase profitability by manipulating the different parameters from the results of this study.

2. Literature Review
There were several studies done that tackled the optimization of CLSC. In the study of Bottani et al. (2020), the concept of optimizing the advantage of the closed loop supply chain (CLSC) that involves suppliers, manufacturers and retailers was investigated. According to their study, CLSCs focus on managing returnable transport items (RTI) or items from customers for some reasons and recuperating the value of an item by reusing it to other items if it does not have defects. These RTIs are used for the internal transport of the products that are ongoing and semi-finished products for the finished products to be distributed (Hajipour et al., 2019). Moreover, they have created a model to optimize the cost of the RTIs in a CLSC and to determine if the system made for the RTIs is effective. They have concluded that their process can be useful for companies who are deciding to change their asset management policy. In the study of Miyamoto and Takeuchi (2019), they summarized various studies about the shift of an alternative source of renewable energy and its impact on the Kyoto Protocol. The result showed that there is a positive effect in efforts to reduce carbon emissions. This led to the use of smart packaging in supply chains. The use of smart packaging could promote sustainability, quality, and safety of products (Chen et al., 2020).

According to Schaefer and Cheung (2020), smart packaging is a modern need for global markers to make the market industry more efficient. It could help the packaging systems that use technology for foods, appliances, and other variety of products. Smart packaging offers various business opportunities such as digitization and fits the standard of modern Industry 4.0. Vanderroost et al. (2014) stated that smart packaging provides a big help to markets because advanced technology is much better as compared to humans. Smart packaging gives assurance to producers up to consumers that the products are guaranteed safe. In the study of Vedove et al. (2021), the concept of smart packaging was used. It is based on the process of cassava starch and a natural pH indicator by a twin-screw extrusion process. The authors discovered that storage temperature and anthocyanin concentration is an important factor for the efficiency of smart packaging. It also informs that smart packages change the quality of the food it contains and one of its predominant models are called self-healing packages (Mlalila et al., 2016). According to Mlalila et al. (2016), as the world progressed through time, there are numerous advancements in the industry in terms of applications and innovations of nanotechnology. Sarkar et al. (2019) stated that self-healing packages help reduce carbon emissions. Moreover, Thomas (2012) conducted studies regarding self-healing packages and stated that it is useful for preservation of materials while minimizing waste products.

According to the Environmental Protection Agency (2018), carbon emission or also known as greenhouse gases are the one of the reasons why the world is at risk for climate change. These emissions are the result of daily human activities that affect the increase of greenhouse gas for over 150 that passed. Mi et al. (2019) stated that the largest cause that triggers greenhouse emissions are the human activities such as the daily transportation, electricity consumption, factories, agriculture, and for residential use. These factors are increasing 3.7% per year that highly affect the environment and economy. Carbon emission is important for this study because according to Sarkar et al. (2016), the supply chain model is considered as a single-supplier, single-manufacturer, and multi-retailer. A total of supply chain cost should be decreased as well as the transportation, system, and carbon emission cost. Carbon emission costs are included due to the multiple deliveries done by a supply chain, transportation of supplies increases and as a result, deliveries contribute greenhouse gas emissions to the environment. Ong et al. (2020) considered direct and indirect carbon emission of a three-level supply chain, optimizing the costs and carbon emission, and carbon tax. The study included carbon tax with regards to the Kyoto Protocol. Results of their study showed that the minimized total cost reduced carbon emission as well. Both industrial and transportation carbon emission and costs were considered (Wangsa, 2017).

The collection of studies above has focused on the optimization of cost in a CLSC managing RTIs, impact of the use of alternative sources of renewable energy to Kyoto Protocol. The emphasis to reduce carbon emission highly focused on the use of smart packaging and self-healing packages. It was determined that RTIs in a CLSC can be of great help for companies who have decided to reform their asset management policy. On a different note, the utilization of renewable energy has resulted a positive effect on reducing carbon emissions. With this, supply chains began to use smart packaging since it promotes sustainability, product safety, and quality. In addition, smart packaging is suitable in the standard of modern Industry 4.0 that is why it offers companies various opportunities. It was found that the efficiency of smart packaging is affected by the storage temperature and anthocyanin concentration. It also tells us that these enhance the quality of food contained in the package, and one of its most notable models are the self-healing packages. Numerous studies have been conducted and have shown that these packages are known to be beneficial for preservation of materials as well as minimization of waste. On the other hand, studies have stated that several human activities like transportation, consumption of electricity, factories, agricultural, and residential use have triggered large carbon emissions. For this reason, studies have included the goal of minimizing carbon emissions in the supply chain. The results of their study have shown that the optimization of cost have also reduced carbon emissions. However, there were no studies that have utilized self-healing packages in their CLSC whose goal is to optimize the total cost and minimize carbon emissions.

3. Methods

3.1 Model Definition

This study was about a three-level closed-loop supply chain considering self-healing packages of a single-supplier, single-manufacturer, and multiple retailers. The model was developed and optimized algebraically considering the overall cost minimization. The model created was in line with the SSMD policy that was practiced by both the supplier and the manufacturer to save the holding cost of multi-retailers. This model was integration of the models from the study of Ong et al. (2020) and Sarkar et al. (2019), focusing on self-healing packages (Figure 1). The model is created for a single product in a closed-loop supply chain under the SSMD policy model. The self-healing packages considered in the model is assumed to have the same state throughout the closed-loop supply chain. There are no shortages allowed in this model. The ordering and holding cost are the same within all retailers. The SSMD policy is followed by both the supplier and manufacturer to save the holding costs along the supply chain (Sarkar et al., 2018). Due to the increase of demand to the product, the holding cost of the inventory becomes greater as it moves through the supply chain. Supply chain's demand is always considered constant. The cycle time is an integer number that is known to be the same from suppliers to manufacturers and to the retailers.

For every player of the system, the costs of the supply chain are developed and are represented in the following sections. As the general summary of the model, the sub-supplier delivers the raw materials to the supplier which is considered as a semi-finished product at a rate of P_s for the manufacturer. The manufacturer will further enhance its finished products using the semi-finished product from the supplier as its raw materials at a rate of P_m, delivered to multiple retailers. Lastly, the manufacturer will then be able to get their inventory materials from the supplier, likewise the retailer to the manufacturer. Figure 1 shows the consideration of the three-level closed-loop supply chain.

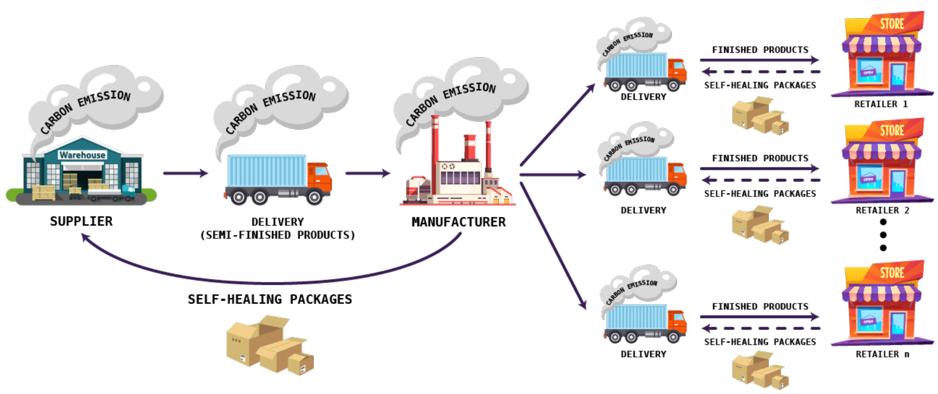

Figure 1. Three-Level Closed-Loop Supply Chain Model

3.2 Mathematical Model

A single-supplier, single-manufacturer, and multi-retailer in a CLSC is designed in the proposed model. In this case, the supplier and manufacturer considered other possible costs such as the raw material ordering cost, production set-up cost, holding cost of raw materials and semi-finished products, packaging procurement and maintenance cost for self-healing packages, and the transportation cost. The considered costs for the multiple retailers consist of ordering cost and inventory holding cost. The sum of all the costs considered in the three-level closed-loop supply chain is seen in Equation 1.

$$
\begin{aligned}
TC(C_T, M_{CT}, R_{CT}, S_R, M_R) &= \left[\frac{C_T}{2}\left(R_{CT}\left(\frac{h_{sr} M_{CT} D^2}{S_R P_s} + \frac{2h_s D^2}{M_R P_s} - \frac{h_s M_{CT} D^2}{P_s} + \frac{h_s D^2}{P_m} + h_s M_{CT} D - h_s D - \frac{h_m D^2}{P_m} + h_m D\right)\right)\right. \\
&\quad \left. + \frac{2h_m D^2}{P_m} - h_m D + h_r D\right] \\
&\quad + \left[\frac{1}{C_T}\left(\frac{1}{R_{CT}}\left(\frac{A_s + O_r S_R}{M_{CT}} + A_m + O_m M_R + M_R F_{s1} + M_R F_{s2} + \frac{S_{m1} D}{X_m}\right)\right) + O_r + F_{m1} + F_{m2} + \frac{S_{s2} D}{X_s}\right. \\
&\quad \left. + \frac{S_{m2} D}{X_m} + \frac{S_{s1} D}{X_s M_{CT} M_R}\right] + DV_{s1(opt)} + \frac{DV_{s2(opt)}}{X_s} + DV_{m1(opt)} + \frac{DV_{m2(opt)}}{X_m}
\end{aligned}
$$

Equation 1. Three-Level Closed-Loop Supply Chain Total Cost

The model considered five decision variables namely, (C_T) regular cycle time to multiple retailers (year), (M_{CT}) manufacturer's cycle time as a multiplier, (R_{CT}) retailer's cycle time as a multiplier, (S_R) inventory received from sub-supplier in a cycle time, and (M_R) inventory received from supplier in a cycle time. To get the least total cost of the decision variables, the model was derived algebraically.

$$TC(C_T, M_{CT}, R_{CT}, S_R, M_R) = C_T(K_1 + K_2) + \frac{A}{C_T} + \alpha_3$$
$$= \frac{\left(C_T\sqrt{K_1 + K_2} - \sqrt{A}\right)^2}{C_T} + 2\sqrt{(K_1 + K_2)(A)}$$

The minimum value was reached by the overall cost equation when the decision variable with respect to C_T is:

$$C_T *= \sqrt{\frac{A}{K_1+K_2}}.$$

The minimum values of the other decision variables were obtained and are as follows:

$$R_{CT} *= \sqrt{\frac{\alpha_2\phi_2}{\psi_2 L}} \qquad M_{CT} *= \sqrt{\frac{\phi_1\,\alpha_1}{H\,\psi_1}} \qquad S_R *= \sqrt{\frac{h_{sr}D^2A_S}{P_S\psi_0 O_S}} \qquad M_R *= \sqrt{\frac{2h_{sr}D^2y}{\phi_{15}Z}}.$$

The expected joint total cost for the optimized equation is seen in Equation 2.

$$EJTC = 2\sqrt{(h_{sr}D^2A_s)(P_s\psi_0 O_s)} + 2\sqrt{(\phi_{15}Z)(2h_{sr}D^2y)} + J + \alpha_3$$

Equation 2. Expected Joint Total Cost

3.2 Variable Notation

$$\Psi_0 = h_s D\left(1 - \frac{D}{P_s}\right)$$

$$\Psi_1 = \frac{h_{sr}D^2}{S_R P_s} + \Psi_0$$

$$\propto_1 = \frac{2h_{sr}D^2}{M_R P_S} + \frac{h_s D^2}{P_m} - h_s D - \frac{h_m D^2}{P_m} + h_m D$$

$$\Psi_2 = M_{cr}\Psi_1 + \propto_1$$

$$\propto_2 = \frac{2h_m D^2}{P_m} - h_m D + h_r D$$

$$K_1 = \frac{R_{CT}\Psi_2 + \propto_2}{2}$$

$$K_2 = \frac{\propto_2}{2}$$

$$X = \propto_2 \emptyset_1 \Psi_1 L + LH \propto_2 \propto_1$$

$$L = O_r + F_{m1} + F_{m2} + \frac{S_{s_2}D}{X_s} + \frac{S_{m_2}D}{X_m} + \frac{S_{s_1}D}{X_s M_{CT} M_R}$$

$$\emptyset_1 = A_s + O_s S_R \qquad \emptyset_{15} = O_m + F_{s1} + F_{s2}$$

$$\emptyset_2 = \frac{\emptyset_1}{M_{CT}} + A_m + M_R\emptyset_{15} + \frac{S_{m1}D}{X_m}$$

$$A = \frac{\emptyset_2}{R_{CT}} + O_r + F_{m1} + F_{m2} + \frac{S_{s_2}D}{X_s} + \frac{S_{m_2}D}{X_m} + \frac{S_{s_1}D}{X_s M_{CT} M_R}$$

$$\propto_3 = DV_{S1(opt)} + DV_{m1(opt)} + \frac{DV_{s2(opt)}}{X_s} + \frac{DV_{m2(Opt)}}{X_m}$$

$$H = A_m + M_R\emptyset_{15} + \frac{S_{m1}D}{X_m} \qquad Y = A_m + \frac{S_{m1}D}{X_m}$$

$$Z = \frac{h_s D^2}{P_m} - h_s D - \frac{h_m D^2}{P_m} + h_m D$$

$$J = \frac{2A_s h_{sr} D^2 \emptyset_{15} \Psi_0}{P_s} + YZA_s\Psi_0$$

4. Data Collection

The data needed for the interpretation of the model were adapted from the study of Ong et al. (2020) and Sarkar et al. (2019) as seen in Table 1. It was utilized in order to find the total cost functions expectation considering the decision variables of the three-level closed-loop supply chain following the SSMD policy. The mathematical model developed to find the best outcome of the sustainable supply chain was translated into this section. This study utilized the Maple Software to obtain the derivation and least total cost.

Table 1. Numerical example data

Parameters	Supplier	Manufacturer	Retailer
Production rate	P_s =2990 units/yr.	P_m =1900 units/yr.	-
i_{th} retailer's demand rate	-	D_m =100 units	-
Ordering costs	O_s =\$300 / order	O_m =\$150/order	O_r =\$30/order
Setup cost	A_s =\$500/setup	A_m =\$200/setup	-
Shipment package capacity	X_s =4 units	X_m =7 units	-
Fixed transportation cost (forward logistics)	F_{s1} =\$15/shipment	F_{m1} =\$12/shipment	-
Fixed transportation cost (reverse logistics)	F_{s2} =\$15/shipment	F_{m2} =\$12/shipment	-
Self-healing package purchase price	S_{s1} =\$0.5/unit	S_{m1} =\$0.4/unit	-
Self-healing packages maintenance cost after return	S_{s2} =\$0.01/unit	S_{m2} =\$0.009/unit	-
Finished Product Holding Cost	h_s =\$0.6/unit/yr.	h_m =\$5/unit/yr.	\$5/unit/yr.
Raw Material Holding cost	h_{sr} =\$0.4/unit/yr.	-	-
Variable transportation cost (forward logistics)	V_{s1} =\$0.1/unit product shipped	V_{m1} =\$5/unit empty package shipped	-
Variable transportation cost (reverse logistics)	V_{s2} =\$0.1/unit product shipped	V_{m2} =\$5/unit empty package shipped	-

5. Results and Discussion

5.1 Numerical Results

This model focuses on the overall cost of a three-level closed supply chain that only considers self-healing packages. As seen in Table 2, M_{CT} is 2, R_{CT} is 2, S_R is 1, and M_R is 5, and the cycle time, C_T is 1.439413. This gives the lowest optimal overall cost to be 1990.952498.

Table 2. Optimal Total Cost

M_{CT}	R_{CT}	S_R	M_R	C_T	Total cost
1	1	1	5	1.439413	2220.845873
1	2	1	5	1.439413	1997.726956
2	1	1	5	1.439413	2079.319019
2	**2**	**1**	**5**	**1.439413**	**1990.952498**

5.2 Sensitivity Analysis

A sensitivity analysis was performed among the various key parameters as shown in Table 3 to determine the range of effect of changing different parameters of the mathematical model. These parameters were the ordering costs, set-up costs and holding costs by the manufacturer together with the retailer's holding cost. In addition, parameters considered for both the manufacturer and the supplier were the cost of purchasing self-healing packages, the cost of maintenance of self-healing packages after return, the capacity of the shipping package, the forward and reverse fixed logistics transport costs, and the supplier's forward and reverse logistics variable transportation cost was only considered. The percentage changes considered were -75, -50, -25, +25, +50, and +75.

Table 3. Sensitivity Analysis

Parameter	% Change	Result (%)	Parameter	% Change	Result (%)
O_m	-75	-10.88	S_{s2}	-75	-0.009
	-50	-7.001		-50	-0.006
	-25	-3.38		-25	-0.003
	25	3.38		25	0.003
	50	7.001		50	0.006
	75	10.88		75	0.009
A_m	-75	-2.69	X_s	-75	16.16
	-50	-1.78		-50	6.04
	-25	-0.88		-25	2.10
	25	0.88		25	-2.10
	50	1.78		50	-6.04
	75	2.69		75	-16.16
h_m	-75	-9.69	F_{s1}	-75	-0.99
	-50	-6.26		-50	-0.66
	-25	-3.03		-25	-0.33
	25	3.03		25	0.33
	50	6.26		50	0.66
	75	9.69		75	0.99
h_r	-75	-23.21	F_{s2}	-75	-0.99
	-50	-14.36		-50	-0.66
	-25	-6.70		-25	-0.33
	25	6.70		25	0.33
	50	14.36		50	0.66
	75	23.21		75	0.99
S_{m1}	-75	-0.007	$V_{s1(opt)}$	-75	-0.38
	-50	-0.005		-50	-0.25
	-25	-0.002		-25	-0.13
	25	0.002		25	0.13
	50	0.005		50	0.25
	75	0.007		75	0.38
S_{m2}	-75	-0.005	$V_{s2(opt)}$	-75	-0.09
	-50	-0.003		-50	-0.06
	-25	-0.002		-25	-0.03
	25	0.002		25	0.03
	50	0.003		50	0.06
	75	0.005		75	0.09
X_m	-75	0.05	F_{m1}	-75	-0.45
	-50	0.02		-50	-0.30
	-25	0.005		-25	-0.15
	25	-0.005		25	0.15
	50	-0.02		50	0.30
	75	-0.05		75	0.45
S_{s1}	-75	-0.005	F_{m2}	-75	-0.45
	-50	-0.003		-50	-0.30
	-25	-0.002		-25	-0.15
	25	0.002		25	0.15
	50	0.003		50	0.30
	75	0.005		75	0.45

As seen from the results, the increasing value of S_{m1}, S_{m2}, S_{s1}, S_{s2}, and V_{s2} would cause a minimal change for the total cost of the closed-loop supply chain. It can also be noted that in any case, increasing the values of these parameters also increases the overall cost of the entire supply chain. This shows equal sensitivity when it comes to positive and negative changes. This is because they lie in the equilibrium position that considers the yearly overall cost of the closed-loop supply chain (Ong et al., 2020).

However, it could also be seen in Table 3 that the changing values of O_m, A_m, h_m, h_r, F_{s1}, F_{s2}, V_{s1}, F_{m1}, and F_{m2} cause huge change to the total cost. These findings can be supported by several studies considering these parameters. According to Tarver (2020), the ordering cost of inventory increases the holding cost of a company while ordering smaller amounts of inventory more frequently increases a company's setup costs. This results in the amend increase of the total cost of a supply chain.

Moreover, based on Mlalila (2016) study, self-healing packages are one of the innovations done in the industry using nanotechnology and are utilized to reduce carbon emission (Sarkar et al., 2019). With this being considered, it can be concluded that an increase in the cost of purchase and maintenance of these kinds of packages will cause a large increase in the total cost of a supply chain. Lastly, Redbird Logistics Services indicated that forward logistics deals with the flow of products starting from raw materials from the sub-supplier, to the supplier, to the manufacturer, and to the retailers which includes hub services, direct order fulfillment, and shipping. Hence, the impact of these methods will increase the value that will be applied to the product as it goes through each step in a supply chain.

As seen in the sensitivity analysis, the increasing values of X_m and X_s causes a decrease in the total cost. Increasing shipment package capacity for both the supplier and manufacturer has been found to reduce the quantity of depots used, leading to decrease in the overall cost (Saif-Eddine et al., 2018). In this case, it is not necessary for the full utilization of the shipment to take place at the lowest overall expense, as increasing shipment package capability would lead to a reduction in the use of the shipment.

The key parameters that went through sensitivity analysis would be the considered factors in attempting to manipulate the overall cost from the proposed closed-loop supply chain system. This could be applied to any part of the demonstrated three-level closed-loop supply chain. The proposed model could be utilized by industries and managers to help all players of the sustainable supply chain minimize the total cost they spent while running the system.

5.3 Proposed Improvements

This mathematical model followed the Kyoto Protocol and could be used by a three-level closed-loop supply chain that considers self-healing packages in real-life applications as well. These packages have polymeric structures that are self-healing and can recover largely spontaneously or with the application of an external stimulus after damage (Sarkar et al., 2019). Because of this, many researchers have seen the application of these materials in various scientific areas. These self-healing packages, especially in the field of food packaging, have potential applications in the industry (Sarkar et al., 2019).

Apart from the optimization of the three-level closed-loop supply chain considering self-healing packages, some limitations were still encountered. These include uncertainties regarding packaging costs, disruptions that occurred in the CLSC network, and unaddressed prioritized shipment schedules. For these reasons, this study can be expanded in various directions including multi-delay in payment, multi-period considerations, multi-supplier, multi-manufacturer CLSC, and asymmetric demand information (Sarkar et al., 2018). In addition, the mathematical model can also be more briefly discussed in different real-life scenarios by future researchers by incorporating the different cases of lead time having greater than or less than permissible payment delay among the different parties of the supply chain (Sarkar et al., 2018). With the application of various cases that Sarkar et al. (2018) did, the generated mathematical model could be further enhanced.

As for managerial insights, the model could be used by manipulating the different parameters such as the ordering costs, set-up costs, holding costs, purchase price and maintenance cost of self-healing packages, forward and reverse logistics transportation cost, and forward logistics variable transportation costs since any increase in these can cause an amend inflation of the total cost of the supply chain. In addition, optimum minimization of the total cost would be attained if the package shipment capacity is immensely greater than the parameters. In this case, not only the optimal cost would be affected, but also the sustainability of the supply chain, which would be beneficial to the environment due to a greener production. Lastly, self-healing packages, a new innovative application to promote environmentally friendly packaging should be utilized and applied by industry managers since it can increase materials' lifespan, reduce replacement costs, and improve product safety (Aissa, 2011).

6. Conclusion

This study was able to develop a mathematical model of a three-level closed-loop supply chain that considers self-healing packages as the main transport packaging under the SSMD policy. In this model, the optimization of the total cost will also optimize the total carbon emissions, making the supply chain sustainable since the model was majorly adapted from the papers of Sarkar et al. (2019) and Ong et al. (2020). With this in mind, there are different parameters that greatly affect the total cost of the mathematical model created for this study. These were the ordering costs (O_m), setup costs (A_m), holding costs (h_m, h_r), purchase price and maintenance cost of self-healing packages ($S_{s1}, S_{s2}, S_{m1}, S_{m2}$), forward and reverse logistics fixed transportation costs ($F_{s1}, F_{s2}, F_{m1}, F_{m2}$) and forward logistics variable transportation cost (V_{s1}). The key reasons why these parameters significantly impacted the three-level closed-loop supply chain considering self-healing packages were: (1) the ordering cost of inventory increases the holding cost of a company while otherwise increases setup costs. (2) A self-healing package requires a huge amount of purchase and maintenance cost. (3) forward and reverse logistics have high transportation costs due to different processes done in each transport.

References

Aissa, B., Therriault, D., Haddad, E., and Jamroz, W., Self-healing materials systems: Overview of major approaches and recent developed technologies, *Advances in Materials Science and Engineering,* vol. 2012, November 25, 2011.

Bottani, E., Montanari R., Rinaldi, M., and Vignali, G., Modeling and multi-objective optimization of closed loop supply chains: A case study, *Computers & Industrial Engineering*, vol. 87, pp. 328-342, 2015.

Chen, S., Brahma, S., Mackay, J., Cao, C., and Aliakbarian, B., The role of smart packaging system in food supply chain, *Concise Reviews & Hypotheses in Food Science,* vol. 85, no. 3, pp. 517-525, February 13, 2020.

Deen, A., An introduction to creating a closed-loop supply chain, Available: https://www.business2community.com/product-management/introduction-creating-closed-loop-supply-chain-01764268#:~:text=Instead%20of%20only%20focusing%20on,resources%20and%20produces%20less%20waste., January 26, 2017.

Dou, Y., Zhou, A., Pam, T., Han, J., Wei, M., Evans, D. G., and Duan, X., Humidity triggered self-healing films with excellent oxygen barrier performance, *Chemical Communications*, vol 50, no. 54, pp. 7136-7138, 2019.

Environmental Protection Agency, Sources of greenhouse gas emissions, Available: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions, 2018.

Hajipour V., Tavana, M., Di Caprio, D., Akhgar, M., and Jabbari, Y., An optimization model for traceable closed-loop supply chain networks, *Applied Mathematical Modeling*, vol. 71, pp. 673-699, 2019.

Kumar, N. R. and Kumar, R. M. S., Closed loop supply chain management and reverse logistics-a literature review, *International journal of engineering research and technology,* vol. 6, no. 4, pp. 455-468, 2013.

Lindsey, R., Climate change: Atmospheric carbon dioxide, Available: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide, August 14, 2020.

Maamoun, N., The Kyoto protocol: Empirical evidence of a hidden success, *Journal of Environmental Economics and Management*, vol. 95, pp. 227-256, 2019.

Mi, Z., Zheng, J., Meng, J., Zheng, H., Li, X., Coffman, D., Woltjer, J., Wang, S., and Guan, D., Carbon emissions of cities from a consumption-based perspective, *Applied Energy*, vol. 235, pp. 509-518, 2019.

Miyamoto, M., Takeuchi, K., Climate agreement and technology diffusion: Impact of the Kyoto Protocol in international patent applications for renewable energy technologies, *Energy Policy*, vol. 29, pp. 1331-1338, 2019.

Mlalila, N., Kadam, D. M., Swai, H., and Hilonga A., Transformation of food packaging from passive to innovative via nanotechnology: *Concepts and critiques*, PMC, vol. 53, no. 9, pp. 3395–3407, 2016.

Ong, A. K. S., Robielos, R. A. C., Jou, Y. T., and Wee, H. M., Three-level supply chain considering direct and indirect transportation cost and carbon emissions, *IOP Conference Series: Materials Science and Engineering*, vol. 847, 2020.

Redbird Logistics Services, What are forward and reverse logistics, Available: https://redbirdlogisticsservices.com/what-are-forward-and-reverse-logistics/, 2019.

Ruz, C., The six natural resources most drained by our 7 billion people, Available: https://www.theguardian.com/environment/blog/2011/oct/31/six-natural-resources-population¸ October 31, 2011.

Saif-Eddine, A. S., El-Beheiry, M. M., and Kharbotly, A. K., An improved genetic algorithm for optimizing total supply chain cost in inventory location routing problem, *Ain Shams Engineering Journa*l, *vol.*10, pp. 63-76, 2019

Sarkar, B., Ganguly, B., Sarkar, M., and Pareek, S., Effect of variable transportation and carbon emission in a three-echelon supply chain model, *Transportation research part e: Logistics and transportation review*, vol. 91, pp. 112-128, 2016.

Sarkar, B., Ahmed, W., and Kim, N., Joint effects of variable carbon emission cost and multi-delay-in-payments under single-setup-multiple-delivery policy in a global sustainable supply chain, *Journal of Cleaner Production*, vol. 185, pp. 421-445, 2018.

Sarkar, B., Tayyab, M., Kim, N., and Habib, M. H., Optimal production delivery policies for supplier and manufacturer in a constrained closed-loop supply chain for returnable transport packaging through metaheuristic approach, *Computers & Industrial Engineering*, vol. 135, pp. 987-1003, 2019.

Schaefer, D. and Cheung, W. M., Smart packaging: Opportunities and challenges, *Procedia CIRP,* vol. 72, pp. 1022-1027, 2018.

Tarver, E., How is the economic order quantity model used in inventory management?, Available: https://www.investopedia.com/ask/answers/052715/how-economic-order-quantity-model-used-inventory-management.asp, September 3, 2020.

Thomas, G. P., Self-healing materials-the future of repairs, Available: https://www.azom.com/article.aspx?ArticleID=7902, November 30, 2012.

Vanderroost, M., Ragaert, P., Devlieghere, F., and De Meulenaer, B., Intelligent food packaging: The next generation, *Trends in Food Science & Technology,* vol. 39, no. 1, pp. 47-62, September 2014.

Vedove, T. M., Maniglia, B. C., and Tadini, C. C., Production of sustainable smart packaging based on cassava starch and anthocyanin by an extrusion process, *Journal of food engineering*, vol. 289, 2021

Wangsa, I., Greenhouse gas penalty and inventive policies for a joint economic lot size model with industrial and transport emissions, *International Journal of Industrial Engineering Computations*, vol. 8, pp. 453-480, 2017.

Zadjafar, M. A., and Gholamian, M. R., A sustainable inventory model by considering environmental ergonomics and environmental pollution, case study: Pulp and paper mills, *Journal of Cleaner Production,* vol. 199, no. 20, pp. 444-458, October 20, 2018.

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