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# Bullwhip effect on closed-loop supply chain considering lead time and return rate: A study from the perspective of Bangladesh

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A B S T R A C T

Continuously increased order and variability of the inventory in the uppermost level of the supply chain node create the Bullwhip effect. In the context of closed-loop supply chains, this dynamic phenomenon is still little understood despite modern nations' increasing interest in exploring the potential for a circular economy. The problem-specific literature has produced results that are a little bit contradictory. I derive formulas in four archetypes for computing inventory order and variance amplification with different information transparency structures to better understand the Bullwhip Effect in the closed-loop structure. It's interesting to note that the visibility of the supply chain's degree significantly influences how lead time and return rate affect the performance of that system. From this vantage point, I may review differences from earlier studies. Later on, I switched the perspective of the study from operational to economic. Here, the ideal return rate was established, and the four closed-loop supply chain (CLSC) archetypes where it might be expressed were provided. I demonstrate that the lead times, demand unpredictability, and the cost structure of all nodes affect the ideal rate of return. In this study, I also address pertinent management implications and the properties of various closed-loop systems from the perspective of Bangladesh.

## 1. Introduction

The amplification of the variability of the customer's order to get closer to the manufacturing echelons is made by the Bullwhip effect. This effect is a very common phenomenon related to operations management. The factory production system and distribution from different supply chain sources are highly connected to this effect pattern. In the 1900s and earlier 2000s, several research studies have shown the connection of logistics with this effect (Chen, Drezner, et al., 2000; Chen, Ryan, et al., 2000). Some expressed the butterfly effect collaborating with this (Lee et al., 1997, 2000; Metters, 1997). Most of the research focused on quantifying the effect on the total supply chain for a certain product or production system (Dejonckheere et al., 2003a, 2003b). Now, this topic is consolidated with the operations research field. Wang & Disney (2016) have shown the direction and progress of the research for this particular field in recent times, where an empirical study with the consultation of analysis for contemporary basis with this dynamic and complex phenomenon was done by Isaksson and Seifert (2016). In recent times, only a little research has shown the investigation of the bullwhip effect in the closed-loop supply chain (CLSC) on an intensive basis. Some previous work was connected to the quantification, estimation, and modification of the existing model related to that effect. Since this effect is highly connected to this type of supply chain loop setting. This will drive the circular economy through the remanufacturing of the product. The collection and remanufacturing or recovery process of the used product will drive them to the structure of a circular economy. This research work distinctly focused on that part. This strategy is highly important because the recovery and collection process of certain products will benefit the business's environmental and economic context. These sides are connected to the cost in different ways. If the lead times of various phases of the whole process can be considered and the return rate through remanufacturing can be increased through the research, the amount of the total cost can be minimised. This process will finally affect the Bullwhip effect for CLSC. The economic opportunity was discussed by Reimann et al. (2019), Govindan

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et al. (2015), Guide et al. (2003), and Genovese et al. (2017). Different challenges and opportunities were discussed in their research work. For the approximation of the bullwhip effect, identification of the ratio was done by Wang & Disney (2016), where both open and closed-loop structures with different constraints were in consideration. Braz et al. (2018) discussed the system of production and distribution that affects efficiency based on the principles of circular economy. The dynamics of this kind of system with meaningful insights were explained by Tang and Naim (2004) of that time to Hosoda and Disney (2018), Ponte et al. (2019), and Zhou et al. (2017) of recent years. Among all of them, several researchers drew a conflicting conclusion. Now, we have tried to find the impact of remanufacturing or reverse product flow in a closed-loop supply chain network considering the rate of product return and lead time, which the previous researcher did not implement. Other relevant discrepancies were also taken into account when conducting this research.

## 2. Literature Review

Variations in the orders and inventory of the closed-loop supply chain structure can be measured using the bullwhip effect, as in traditional supply chain networks. Initially, dynamic behaviour concerning operational costs was absent in the research (Cannella & Bruccoleri, 2013; Disney & Lambrecht, 2007). From the research of Goltsos et al. (2019), three distinct domains were found to explore the impact of the bullwhip effect concerning the closed-loop supply chain. Firstly, the impact of the rate of return of the remanufactured product is expressed by comparing the operational performance. Secondly, the effect of the lead time in different states of total manufacturing techniques for both forward and reverse type flow for the materials creates the paradox of the lead time. Thirdly, the impact of the level of transparency of the information throughout the entire closed-loop supply chain that incorporates traditional models related to inventory.

For the investigation of the impact of the return rate on the closed-loop supply chain structure, most of the research papers drew the positively mentioned consequences of the increase of the rate to reduce the number of orders and their visibility (Cannella & Bruccoleri, 2013.; Dev et al., 2017; Tang & Naim, 2004; Zhou & Disney, 2006). Some research was connected to some interesting assumptions. An increase in the lower rate of return works to mitigate the Bullwhip effect, as shown by Adenso-Díaz et al. (2012). This study found a U-shaped relationship between the effect and return rate. Zhou et al. (2017) concluded the dynamics of the multi-echelon closed-loop supply chain network considering the benefit of the reverse flow of the material throughout the network area. They concluded that a closed-loop creates magnifications in the bullwhip effect compared to the open-loop scenario, i.e., closed-loop network dynamics generate more benefits than traditional ones. Hosoda & Disney (2018) claimed that the bullwhip effect is more likely connected to closed-loop supply chain networks due to its wider uncertainties scenario. Ponte et al. (2019) observed it from a different viewpoint. They explained that the return rate correlated with the independent component concerning the created demand would be inversely proportional to the system's dynamics. These studies are aligned with Dominguez et al. (2019) and Hosoda & Disney (2018), who observed that order visibility and inventory are more sensitive to uncertainties with the closed-loop network on the return in the future. This will result in poor operational and economic performance in the entire network. Their discussion expressed that the implication of return rate with the modelling assumption is highly sensitive to the closed-loop dynamics. The return rate is also discussed in traditional network settings. Different linear and non-linear models for the production and distribution system were built based on the assumption of returning the stock to the initial nodes without making any extra cost (Chatfield & Pritchard, 2013; Ponte et al., 2019). They not only create models but also explore these returns for unused products and create dynamic models for serial types of supply chains. Additionally, a divergent and more robust supply chain with real-time assumption of product return was shown by Dominguez et al. (2015). The nature of the supply chain structure was different, and the dynamics of the return process emerged in this type of research work.

The forward-type flow of the materials was considered to determine the influence of the lead time in a closed-loop supply chain network setting. For example, the reduction of the manufacturing lead time concerning the order variabilities and level of inventory was derived from the research of Zhou & Disney (2006). Smooth production and distribution to satisfy the customer with high-cost effectiveness were ensured by shortening the lead time required. In the reverse flow of the materials, lead time can affect the remanufacturing process, a vital part of the entire process. Some research expressed the impact of reducing manufacturing lead time on operational and economic growth (Cannella et al., 2016; Zhou et al., 2017; Zhou & Disney, 2006). Nevertheless, this research discovered a lead time paradox with the setting to reduce the lead time required for remanufacturing. This was also found in the closed-loop setting (Inderfurth & Van Der Laan, 2001). Variability matrix for inventory level in terms of effect of bullwhip was observed by Tang & Naim (2004) in their models. They additionally ensured the highest level of transparency of information. Hosoda et al. (2015) expressed that inventory dynamics may be affected by the time required for the cutting remanufacturing. Hosoda & Disney (2018) proved that it can also occur through the variability matrix for the order. In detail, the paradox was investigated later and revealed that it would happen only when remanufacturing takes comparatively less time than manufacturing. The policy maintained for an order is not that effective for the information of the reverse material flow. Determination of the lead time for stochastic and deterministic type remanufacturing was done using the study of Dominguez et al. (2019). They also detected the paradox. So, the impact of lead time in closed-loop supply networks was treated as a fundamental assumption that these researchers expressed.

Several previous research studies were performed to determine the impact of information transparency. Different strategies related to information sharing were quantified in some of them to assess information transparency. Tang & Naim (2004) developed three different supply chain models where various information-sharing degrees were developed. The conclusion drawn by Cannella et al. (2016) was the same, but they considered multiple inventory models and created a difference in information sharing. Hosoda et al. (2015) explored that managing the serviceable inventory can dramatically improve manufacturers' work-in-process (WIP). They also discussed the notice return scheme connected to the inventory. The considerations in reducing the amount and values of information will create the uncertainties discussed by (Ponte et al., 2019). He suggested a mechanism related to controlling the reverse flow mechanism for the materials, which regulates returns inventory.

Recently, Zhu et al. (2020) dealt with the bullwhip effect on the supply chain network related to gas and oil. Goel et al. (2020) investigated the impact of the bullwhip effect by analysing different types of papers related to closed loop structure, where the coordination mechanism associated with this issue was determined by Ran et al. (2020) using various digital technologies. The causes and mitigation strategies of this effect in closed-loop environments were explained in a research work (Feng, 2023). Inhibitory influence concerning the difference of feedback was considered by Gao et al. (2024) whereas, quantification of the effect was investigated in several papers (Almaktoom, 2024; Dolgui et al., 2020; Durán Peña et al., 2021; Pournader et al., 2023 and Rahman et al., 2020).

Some of the research work was performed in this particular field from the perspective of Bangladesh. For example, the causes, mitigation strategy, and intensity of the bullwhip effect in the closed-loop supply chain of Bangladeshi products were explored by Rahman et al. (2020). Similarly, Rashed et al. (2023) studied the consequences of this effect concerning Dhaka City, Bangladesh's boutique industry. A similar analysis was performed for a befitting supply chain considering the apparel industry by Islam Fahim et al. (2020). The perishable supply chain was supposed to be sustainable by mitigating the bullwhip effect by maximising the quality and minimising the waste was a major topic of the research of Durán Peña et al. (2021) and Shareef et al. (2024) from the perspective of the Bangladeshi supply chain.

From this overall analysis, there is some confusion about closed-loop supply chain visibility value from the perspective of the bullwhip effect. From the prior studies focused on this review, it is clear that information transparency is highly connected to this research work. Other relevant factors are vital in determining and enhancing the system's operational and economic performance. Visibility modifies the lead time and return rate and greatly impacts closed-loop supply chain networks, which have not yet been considered. From Goltsos et al. (2019) and Ponte et al. (2020), a clear direction can be found to better understand the importance of the Bullwhip effect in the real closed-loop supply chain system. Table 1 represents the summary of the literature review.

**Table 1**
Summary of the literature review.

| Reference | Applied Methods | Types of Logistics | | Types of Loops | | | Other Assumptions | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | FL | RL | OL | CL | CI | MS | PA | LT | RR | IT |
| Cannella & Bruccoleri (2013) | Exponential smoothing Forecast | ✓ | | | ✓ | | | | | | |
| Goltsos et al. (2019) | Control Theory Approach | ✓ | | | ✓ | | ✓ | | | | ✓ |
| Dev et al. (2017) | Strategic inventory design | | ✓ | | ✓ | | ✓ | | | | |
| Tang & Naim (2004) | Systematic Literature Review | | | | ✓ | | ✓ | ✓ | | | |
| Zhou & Disney (2006) | Variance amplification and golden ratio | | | ✓ | | | ✓ | ✓ | | | |
| Cannella et al. (2016) | Order Replenishment Rule | | ✓ | | ✓ | | ✓ | | | | |
| Zhou et al. (2017) | Supply chain models | | | ✓ | | | ✓ | | | | |
| Dominguez et al. (2019) | System Dynamics | | | | ✓ | | ✓ | | | | |
| Dominguez et al. (2015) | Network configuration design | | ✓ | | ✓ | | ✓ | ✓ | | | |
| Chatfield & Pritchard (2013) | Dynamics of remanufacturing systems | | | | ✓ | | | | | | ✓ |
| Ponte et al. (2019) | Different optimisation models | | | | ✓ | ✓ | ✓ | ✓ | | | |
| Hosoda et al. (2015) | Control Engineering | | | | | | ✓ | | | | |
| Goel et al. (2020) | Correlation determination | | | | ✓ | | ✓ | ✓ | | | |
| Zhu et al. (2020) | Stochastic inventory control | | | | ✓ | | ✓ | | | | |
| Ran et al. (2020) | Coordination mechanism | | ✓ | | ✓ | | ✓ | | | | |
| Hosoda & Disney (2018) | Unified Theory | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | |
| Reimann et al. (2019) | MOMIP, FRO, & GP | | | | ✓ | | ✓ | | | | |

**Table 1**
Summary of the literature review (Continued)

| Reference | Applied Methods | Types of Logistics | | Types of Loops | | Other Assumptions | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | FL | RL | OL | CL | CI | MS | PA | LT | RR | IT |
| Govindan et al. (2015) | Comprehensive review | | | | | | | ✓ | | | |
| Guide et al. (2003) | Forecasting techniques | | | | ✓ | | ✓ | ✓ | | | |
| Genovese et al. (2017) | Capacity constraints dynamics | | | | ✓ | | ✓ | | | | |
| Isaksson & Seifert (2016) | Cross-industry empirical investigation | | ✓ | | ✓ | | ✓ | ✓ | | | |
| Tang & Naim (2013) | System dynamics | | | | ✓ | | ✓ | | ✓ | ✓ | |
| Durán Peña et al., (2021) | Hybrid metaheuristic algorithms | | | | ✓ | | | ✓ | | | |
| Dolgui et al. (2020) | Ripple effect | | | | | ✓ | ✓ | | | | |
| Almaktoom (2024) | Inventory variance calculations | | | | ✓ | | ✓ | ✓ | | | |
| Rahman et al. (2020) | Impact Determination | | | | ✓ | ✓ | ✓ | ✓ | | | |
| Rashed et al. (2023) | Risk Preference Models | | ✓ | | ✓ | | ✓ | ✓ | | | |
| Shareef et al. (2024) | Causes and Consequences Determination | | ✓ | | | | ✓ | ✓ | | | |
| Durán Peña et al. (2021) | Mitigation Countermeasure determination | | ✓ | | ✓ | | | ✓ | | | |
| Ponte et al. (2020) | Optimisation models | | ✓ | | ✓ | | ✓ | | | | |
| This Study | Distinct Optimization models | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

Notations: FL: Forward Logistics; RL: Reverse Logistics; OL: Open Loop; CL: Close Loop; CI: Cause Identification; MS: Mitigation strategy; PA: Performance Analysis; LT: Lead Time; RR: Return Rate; IT: Information Transparency.

## 3. Structure of the work

From the above discussion, we can gather the idea that the closed-loop supply chain's operational performance will help to determine the dynamic behaviour of the Bullwhip effect over the information-sharing strategy. The important relational gap between these two factors should be met. Analytic type expressions were derived here in this research, and some equations were found. This performance depends on how the lead time, return stock and level of information transparency are connected to the bullwhip. This is for the Bullwhip ratio presented by $B_{r,}$ and the Net stock Amplification ratio expressed by $NSA_r$ in a closed-loop supply chain context. Four archetypes were considered for the two visible dimensions of hybrid manufacturing. One is the pipeline of remanufacturing, and the other is the pipeline of markets. The first one is the return visibility collected by the remanufacturer but not to be received by the inventory site on hand. The next one is the visibility of products sold and accepted by the supply chain network. Several properties were identified to define the effect of the performance on the lead time, rate of return, and degree of information transparency. They are presented below:

1. The increment of the return volume in this particular system will improve the dynamics of a closed-loop supply chain system.
2. The smoothing criteria for manufacturing operations will increase the visibility of the remanufacturing pipeline.
3. Relatively less inventory performance will be found from closed-loop settings than traditional ones.
4. Net stock variability will be reduced for the visibility of the work in the process of the remanufacturers. Rather, the lead time for manufacturing is much smaller than the lead time required for remanufacturing.
5. The lead time for remanufacturing will reduce the performance of the inventory. For this reason, lead time paradoxes will appear in some cases. The variability of the closed-loop supply chain order will be presented as the result of the order's visibility in the marketplace.

Then, the economic perspective of the $B_r$-$NSA_r$ in the setting of a closed-loop and the investigation of optimising the supply chain by focusing on lead time and return rate will be performed. So, an understanding of the bullwhip phenomenon is necessary.

The article is organised as follows: The next section represents the closed-loop supply chain setting with the proper assumption of four archetypes differing in visibility. Then, four phases describe the expressions related to $B_r$-$NSA_r$. Section 6 discusses the main findings. The next section performs an economic analysis, investigating the optimal return rate for all archetypes. The last section represents the conclusions and future scope.

## 4. Model Formulation

Several research papers displayed different types of structures used for purposes quite similar to this study (Cannella et al., 2016; Dominguez et al., 2019; Hosoda & Disney, 2018; Ponte et al., 2019; Zhou & Disney, 2006). This study investigated a hybrid system for a closed-loop supply chain, including manufacturing and remanufacturing. In this system, manufacturing will produce serviceable product inventory, and remanufacturing will be performed similarly to manufacturing new products. It should be confirmed that both products will satisfy or meet the customer's demand. This manufacturing structure is followed by many industries nowadays (Goltsos et al., 2019; Souza, 2013)From a Bangladesh perspective, we can consider the spare parts industry. Fig. 1 represents our proposed model. It shows the flow from suppliers to the collection point. There are three phases: manufacturing, serviceable stock, and consumption. Lead time, which consists of the manufacturing phase, will be expressed by $L_A$, and $L_B$ will express the lead time of serviceable stock. $L_C$ will represent the lead time of the consumption phase.

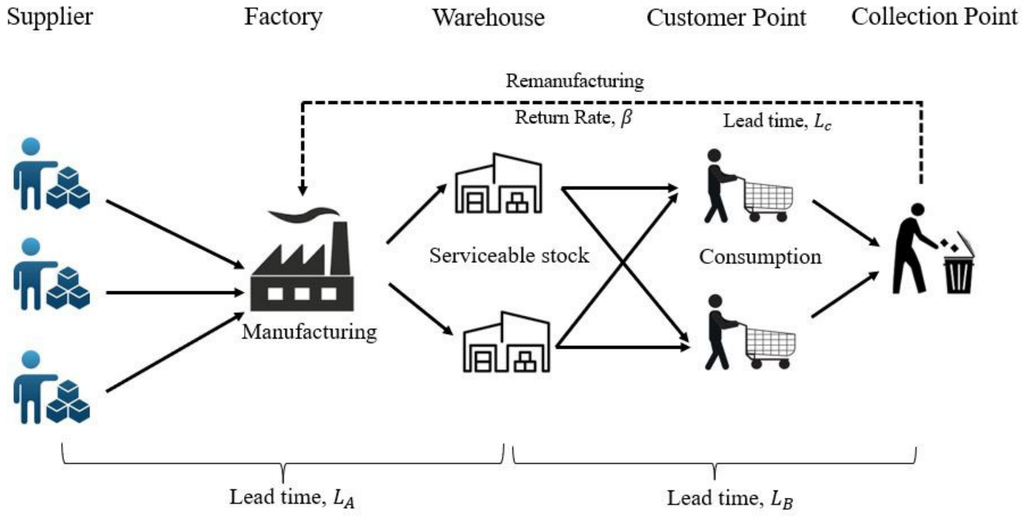

**Fig. 1.** Representation of the proposed model

Remanufacturing will be performed from the collection point to the manufacturing plant. Where the return rate will be expressed by $\beta$. The actual output will be defined using $1-\beta$, which is the manufacturing rate. This process will be repeated to execute the whole manufacturing regularly. This analysis assumed deterministic parameters similar to those of the most important closed-loop supply chain network structures (Adenso-Díaz et al., 2012; Cannella et al., 2016; Zhou et al., 2017)Under different operational conditions, closed analytical equations with key indicators were considered for the model. The information transparencies on this type of loop were used to address the best-case scenario, minimising uncertainties related to these considerations.

The assumption was made to satisfy every period of demand from the consumer side. A certain portion related to demand will be met using the product found in remanufacturing, $s_u$. The remanufactured product will be treated as the used product, expressed by $\beta$, that will be back in the chain within the lead time $L_B$. Then, the remanufacturing facility will be utilised to process it and convert it to a full operational condition with a lead time $L_C$. For the remanufacturing, push policy will be considered based on the collection of the product, which is a common assumption as the research from Goltsos et al. (2019), as well as fits the sustainability ethics of the research study by Hosoda & Disney (2018). A relationship can be formed based on the assumption,

$$s_u = \beta d_{u-L_B-L_C} \tag{1}$$

Manufacturing new products will meet the rest of the demand. A replenishment policy will be employed to manage serviceable stock or serviceable inventory (Disney & Lambrecht, 2007), which was assumed based on a perspective in Bangladesh. They assumed that the manufacturer would place a production order for the newly arrived product at the end of the period. Here, the new product is expressed by $p_u$. To fill the gap between the actual and desired inventory, an order is placed up to the expected point, $T_u$. Then, it was considered that all the inventory would be placed on hand, i.e. serviceable inventory, $j_u$, and work-in-process, which is on-order, $x_u$. Then, the equation can be formed and represented in Eq. (2),

$$\tau_u = T_u - j_u - x_u \tag{2}$$

The amount of product manufactured, $n_u$, which is used to respond based on the order from the production side. Serviceable inventory will receive them after an interval of the manufacturing lead time $L_A$. Therefore, the equation can be formed as,

$$n_u = \tau_{u-L} \tag{3}$$

This scenario will occur in real-time problem analysis of a closed-loop supply chain. It is assumed that lead time related to manufacturing and remanufacturing is relatively less than that of the consumption phase. Cannella et al. (2016) and Ponte et al. (2019) discussed it in their research study. That can be represented as $L_A$, $L_C \ll L_B$.

For the facilities related to manufacturing and remanufacturing, unconstraint-type production capacity is assumed for Eqs. (1-3). It was also considered here that new and newly liked products will be available at the beginning of each period. Serviceable inventory will be made from here and expressed by $j_u$, the difference between the receipt amount for both production processes and the projected product requirement, which means demand. The formula can be written as,

$$j_u = j_{u-1} + n_u + s_u - d_u \tag{4}$$

By following the common notations, $j_u > 0$, which expresses the inventory treated as excess at the end of a period. This will entail a larger storage cost. Alternatively, when, $j_u < 0$, it represents the amount of backlog. This demand won't be fulfilled within a given timeframe, and that will be fulfilled whenever the inventory is refilled.

Independent consumer demand will be considered, which is distributed identically. The random variable with mean $\mu$, and standard deviation, $\sigma$ is considered. Here, $\sigma \ll \mu$. The probability of finding negative demand is very small (negligible). Thus, this study is not limited to normally distributed demand. Independent customers can be assumed, and demand stems from the central limit theorem. (Hedenstierna et al., 2019). Later, it was defined that $\lambda = \sigma^2/\mu$ as the ratio of variance of demand to mean, it is known as the dispersion index. The population means and nature of the series of demands will be calculated accurately, and the manufacturer will be able to perceive it. Based on this condition, fixed forecast value should be used such that, $f_u = \eta$ concerning $\eta = \mu$. This results in a minimum value of mean square error (MSE) (Hosoda & Disney, 2009). This forecast value can be assumed for the time-invariant order to the point, $S_u$ (Ponte et al., 2017).

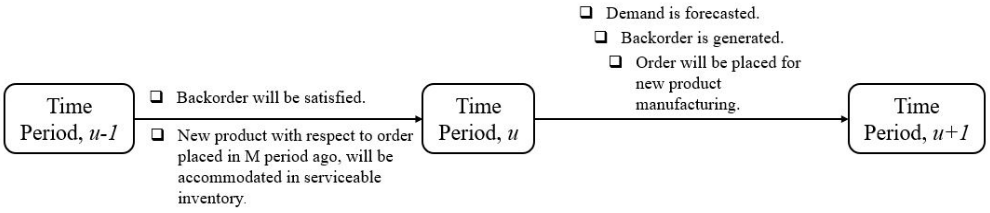

**Fig. 2.** Event sequence for the proposed model**.**

Fig. 2 shows the event sequence for the serviceable inventory of the closed-loop supply chain structure. The backorders will be satisfied if found between periods *u-1* and *u*. The new product will be ordered in the immediate period. Between period *u* and *u+1*, the demand will be estimated, a backorder will be calculated, and an order for a new product will be placed. Eqs. (1-4) describes the mathematical expression for this model. Here, the fundamental relationship was provided. This will be applied to the four archetypes represented in the next section.

## 4. Work-in-progress models

Generally, the work-in-progress concept is fundamental for the open-loop supply chain system. This will cover the ordered product, i.e., in the production system but not received or on hand. Nilakantan et al. (2017) explained it previously. Based on the literature review, all four types of computations for the closed-loop supply chain system were explained here. Four variants are found for the four work-in-process models, and they are labelled as archetypes for our hybrid system with visibility of the supply chain degrees.

The model of this research includes two types of visibility. One is visibility for the remanufacturing pipeline, and another is for market pipeline visibility. The first refers to the returned products; remanufacturers collect them but have not yet received them after their processing. Then, another one refers to the products that are sold. Both types of visibility were categorised based on transparency and opaqueness, depending on whether the manufacturer can access information relevant to the system. A transparent pipeline for the manufacturer was assumed for all of the cases.

Fig. 3 is used to demonstrate the visibility of the dimensions. It is considered based on real-time scenarios. It is important to note that the manufacturer may or may not observe the remanufacturing pipeline. It depends on whether the node is external or internal when remanufacturing operations. Abbey and Guide (2018) proposed the remanufacturing system typology connected to the inclusion of the third party in the industry's operations. Alternatively, in most cases, it is tough to know the exact phase of the product in the market. The trajectory of some products, such as those that are highly expensive or have multiple lifecycles, can be tracked in some circumstances. Exhaustive type control is required for this purpose.

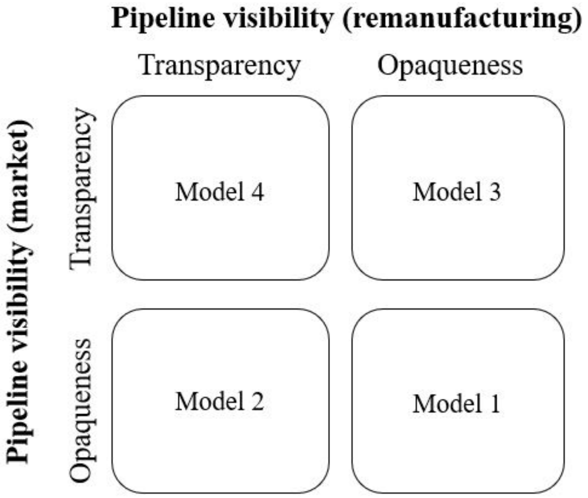

**Fig. 3.** Work-in-progress policies.

For example, the optical product was considered in the study of Goltsos et al. (2019), which used a military-type setting with a strictly controlled system due to the contract's requirement.

### *4.1 Model-1*

This configuration is most common when information from the manufacturer's side is used. So, the work-in-progress can be expressed as, $x_u = x_u^n$. This is the sum of the previous order and the current state's manufacturing receipts. This is the same as the issued order between the time interval *u-1* and *u-(L$_A$-1)*. The equation can be expressed by,

$$x_u = x_u^n = x_{u-1} + \sigma_{u-1} - n_u = \sum_{j=1}^{L_A-1} \sigma_{u-1} \tag{5}$$

Zhou & Disney (2006) discussed this type of model in their research many years ago. They analysed the model performance for them, which is not accessible by the remanufacturer, and information on the market pipeline in a closed-loop supply chain setting.

### *4.2 Model-2*

Remanufacturers' work-in-progress will be considered here in this model type. This will express the improvement of the hybrid system dynamics. Based on the assumption, the remanufacturing pipelines work-in-progress can be described as, $x_u^s$. This is the amount of collected product by the remanufacturers between the time interval *u-(L$_B$-1)* and *u*. This turn is presented by using the return rate, $\beta$, which is the consumption demand for the lead time, *L$_B$*. The work-in-progress can be expressed by, $x_u = x_u^n + x_u^s$. The result of this can be written as,

$$x_u = x_u^n + x_u^s = \sum_{j=1}^{L_A-1} \sigma_{u-1} + \beta \sum_{j=1}^{L_C-1} d_{u-L_B-1} \tag{6}$$

The information potential will enhance the performance of the closed-loop supply chain system. This has been explored by several researchers, such as Cannella et al. (2016) and (Tang & Naim, 2004).

### *4.3 Model-3*

For capturing data on the products present at the market and products that will be returned to the market after being used by customers in a closed loop chain, the same idea of model 2 is applied here for the analysis. Here, the value of the work-in-progress, $x_u^c$, will be computed based on the product return rate $\beta$ and demand value with lead time *L$_B$*. Now, we will consider the case of remanufacturers' work-in-progress. Meanwhile, the manufacturer will consider the market pipeline along with the previous one. Then, the mathematical equation can be written for $x_u = x_u^n + x_u^c$ as,

$$x_u = x_u^n + x_u^s = \sum_{j=1}^{L_A-1} \sigma_{u-1} + \beta \sum_{j=1}^{L_B-1} d_{u-1} \tag{7}$$

This case is the least common among the four, which allows us to complete the picture of a closed-loop structure. The dynamic behaviour of this model will help to find the Bullwhip effect of the supply chain, which we consider to be the most important. Model 3 represents the visibility of model 1. This is the null visibility. However, this model expresses the full transparency of model 4.

### *4.4 Model-4*

Lastly, full visibility of the supply chain is considered here in this model 4. In this work-in-progress model, the remanufacturer and future return pipelines were considered. The first type of pipeline is expressed by $x_u^s$, and $x_u^c$ is used to express the second type. The overall process can be represented as,

$$x_u = x_u^n + x_u^s + x_u^c = \sum_{j=1}^{L_A-1} \sigma_{u-1} + \beta \sum_{j=1}^{L_C-1} d_{u-L_B-1} + \beta \sum_{j=1}^{L_B-1} d_{u-j} = \sum_{j=1}^{L_A-1} \sigma_{u-j} + \beta \sum_{j=1}^{L_B+L_C-1} d_{u-j} \tag{8}$$

Estimation for the future return pipeline, along with their inventory-related hybrid model related to the manufacturing and remanufacturing system, was performed previously by Hosoda et al. (2015) and Hosoda & Disney (2018). They discussed the implications of lead time in enhancing the performance of the supply chain.

This research study analyses and expresses these variants. A set of replenishment approaches is implemented in real-life supply chain-related problems. This study's performance is fully dependent on the degree of available information. Here, the base system is expressed by model 1, which connects with the order-up-to policy. The effect of serviceable inventory is adjusted here. The inventory policy is presented in model 4, which ensures the full visibility of the product in the closed-loop supply chain network system.

## 5. Bullwhip effect and Net Stock Amplification ratio

Two indicators are considered here to analyse the supply chain's dynamic character based on the information transparency structure. This will be considered when defining the supply chain's performance. (Turrisi et al., 2013; Zhou et al., 2017). Firstly, the bullwhip ratio (*B<sub>r</sub>*) will be determined. This is the ratio between the variance of the placed order and the variance of the projected requirement or demand.

$$B_r = \frac{\text{variance of order placed}}{\text{variance of the demand}} = \frac{\sigma_{p_u}^2}{\sigma_{d_u}^2} \tag{9}$$

The bullwhip ratio and the Net stock amplification ratio for the closed-loop supply chain in all four archetypes are presented in Table 2. This ratio expresses the manufacturing lines' stability, which can be assumed to enhance production efficiency. Reduction of the bullwhip ratio, $B_r$ used to enable the production costs associated with the capacity in a particular supply chain system. Then, the Net Stock Amplification ratio, $NSA_r$, is the ratio of the variance of inventory found at serviceable conditions to the projected requirement or demand variance.

$$NSA_r = \frac{\text{variance of serviceable inventory}}{\text{variance of the demand}} = \frac{\sigma_{j_u}^2}{\sigma_{d_u}^2} \tag{10}$$

This will provide information on the system's capacity to satisfy customer demand cost-effectively. It will also improve the trade-off among investments in customer service, inventories, etc.

The expression for the ratios of all four archetype variants is derived here using different equations. A summary of them is presented in Table 1 using the return rate, $\beta$ and lead time of different states such as $L_A$, $L_A$, and $L_C$.

For the calculations of the Bullwhip ratio, $B_r$, firstly, the difference between the placed order of two time periods, which is in consecutive form *u* and *u-1,* is taken into account as,

$$p_u - p_{u-1} = (T_u - T_{u-1}) - (j_u - j_{u-1}) - (x_u - x_{u-1}) \tag{11}$$

In Eq. (11), the order-up-to policy follows the conditions which are time-invariant, which makes $T_u - T_{u-1} = 0$. Additionally, from the Eq. (4), it can be written that, $j_u - j_{u-1} = n_u + s_u - d_u$, where, $n_u = p_{u-L_A}$ and $s_u = \beta$, $d_{u-L_B-L_C}$ found from Eq. (3) and Eq. (1), respectively. Therefore,

$$\begin{aligned} p_u &= p_{u-1} - \left(p_{u-L_A} + \beta d_{u-L_B-L_C} - d_u\right) - (x_u - x_{u-1}) \\ &= \left(d_u - \beta d_{u-L_B-L_C}\right) + \left(p_{u-1} - p_{u-L_A}\right) - (x_u - x_{u-1}) \end{aligned} \tag{12}$$

For obtaining the value net stock amplification ratio, the isolation of on-hand delivery can be represented as,

$$j_u = T_u - p_u - x_u \tag{13}$$

### *5.1 Expressions for model-1*

The Eq. (5) can be represented as, $x_u - x_{u-1} = p_{u-1} - p_{u-L_A}$. Thus, Eq. (12) can be written as,

$$p_u = d_u - \beta d_{u-L_B-L_C} \tag{14}$$

The value of demand is presented as a random variable and not co-related. An inventory-related equation can be formed as,

$$B_r{}^{model-1} = \frac{\sigma^2_{p_u}}{\sigma^2_{d_u}} = \frac{\sigma^2+\sigma^2\beta^2}{\sigma^2} \tag{15}$$

Now, the Net Amplification ratio value should be determined for model 1. Based on the assumption, the equation of inventory can be represented from Eq. (5) and Eq. (14) as,

$$j_u = T_u - \sigma_u - \sum_{j=1}^{L_A-1} \sigma_{u-j} = T_u - \sum_{j=1}^{L_A-1} \sigma_{u-j} = T_u - \sum_{j=1}^{L_A-1} d_{u-j} - \beta d_{u-L_B-L_C-j} \tag{16}$$

Based on the assumptions made for this study, such as, $L_A \ll L_B$ and relevant addends are no longer correlated with each other. For the sum of $L_A$ terms, the value of specific demand and return value, i.e. $(u + L_B + L_C)$ was not considered. For the analysis, $T_u$ was fixed over a particular period. The ratio for net amplification of stock can be presented as,

$$NSA_r{}^{model-1} = \frac{\sigma^2_{j_u}}{\sigma^2_{d_u}} = \frac{L_A\sigma^2+L_A\sigma^2\beta^2}{\sigma^2} = L_A + \beta^2 L_A \tag{17}$$

### *5.2 Expressions for model-2*

For the consecutive periods, the difference between the work-in-progress can be written based on Eq. (6) as, $x_u - x_{u-1} = p_{u-1} - p_{u-L_A} + \beta(d_{u-L_B} - d_{u-L_B-L_C})$. Then, Eq. (12) becomes,

$$p_u = (d_u - \beta d_{u-L_B-L_C}) - \beta(d_{u-L_B} - d_{u-L_B-L_C}) = (d_u - \beta d_{u-L_B}) \tag{18}$$

Bullwhip ratio can be developed based on the characteristics of the demand scenario for certain models as,

$$B_r{}^{model-2} = \frac{\sigma^2_{p_u}}{\sigma^2_{d_u}} = \frac{\sigma^2+\sigma^2\beta^2}{\sigma^2} = 1 + \beta^2 \tag{19}$$

For the calculation of the Net Stock Amplification ratio, work-in-progress will be taken into consideration from Eq. (6) and relational demand from Eq. (18). It can be represented as follows,

$$\begin{aligned} j_u &= T_u - \sigma_u - \sum_{j=1}^{L_A-1} \sigma_{u-j} - \beta \sum_{j=0}^{L_C-1} d_{u-L_B-j} = T_u - \sum_{j=0}^{L_A-1} \sigma_{u-j} - \beta \sum_{j=0}^{L_C-1} d_{u-L_B-j} \\ &= T_u - \sum_{j=0}^{L_A-1} d_{u-j} + \beta \sum_{j=0}^{L_A-1} d_{u-L_B-j} - \beta \sum_{j=0}^{L_C-1} d_{u-L_B-j} \end{aligned} \tag{20}$$

The first part of the Eq. (20) expresses the demand value between the period $u$ and $u - (L_A - 1)$, Then, the next part expresses demand between periods. $u - L_B$ and $u - (L_B + L_C - 1)$. Overlap may occur between the first two parts. So, three different scenarios may be presented to mitigate the conflicting situations.

- $L_C = L_A$, i.e. the lead time for both is equal. Then, the first and second parts will be eliminated from Eq. (20). The equation will be converted into a simplified form, and it can be represented as, $j_u = T_u - \sum_{j=0}^{L_A-1} d_{u-j}$; The *NSA<sub>r</sub>* for the model can be written as follows,

$$NSA_r{}^{model-2} = \frac{\sigma^2_{j_u}}{\sigma^2_{d_u}} = \frac{L_A\sigma^2}{\sigma^2} = L_A \tag{21}$$

- $L_C > L_A$, i.e., the remanufacturing lead time is higher than the manufacturing lead time. Then, the second part will be in the third part of Eq. (20). The equation will be converted into, $j_u = T_u - \sum_{j=0}^{L_A-1} d_{u-j} - \beta \sum_{j=L_A}^{L_C-1} d_{u-L_B-j}$; The $NSA_r$ for the model can be written as follows,

$$NSA_r{}^{model-2} = \frac{\sigma_{j_u}^2}{\sigma_{d_u}^2} = \frac{L_A\sigma^2 + (L_C - L_A) - \sigma^2\beta^2}{\sigma^2} = L_A + \beta^2(L_C - L_A) \tag{22}$$

- $L_C < L_A$, i.e., the manufacturing lead time is higher than the remanufacturing lead time. The equation will be converted into, $j_u = T_u - \sum_{j=0}^{L_A-1} d_{u-j} + \beta \sum_{j=L_C}^{L_A-1} d_{u-L_B-j}$; The $NSA_r$ for the model can be written as follows,

$$NSA_r{}^{model-2} = \frac{\sigma_{j_u}^2}{\sigma_{d_u}^2} = \frac{L_A\sigma^2 + (L_A - L_C) - \sigma^2\beta^2}{\sigma^2} = L_A + \beta^2(L_A - L_C) \tag{23}$$

Based on all these equations, a common expression of the net stock amplification ratio for model 2 can be expressed as follows,

$$NSA_r{}^{model-2} = \frac{\sigma_{j_u}^2}{\sigma_{d_u}^2} = L_A + \beta^2\,|L_A - L_C| \tag{24}$$

*5.3 Expressions for model-3*

For this model, $x_u - x_{u-1} = p_{u-1} - p_{u-L_A} + \beta(d_u - d_{u-L_B})$. The Eq. (7) and (12) will be summarised as follows,

$$p_u = (d_u - \beta d_{u-L_B-L_C}) - \beta(d_u - d_{u-L_B}) = (1-\beta)d_u + \beta d_{u-L_B} - \beta d_{u-L_B-L_C} \tag{25}$$

Then, Bullwhip ratio,

$$B_r{}^{model-3} = \frac{\sigma_{p_u}^2}{\sigma_{d_u}^2} = \frac{\sigma^2(1-\beta)^2 + \sigma^2\beta^2 + \sigma^2\beta^2}{\sigma^2} \tag{26}$$

The Net Stock Amplification ratio,

$$\begin{aligned} j_u &= T_u - \sigma_u - \sum_{j=1}^{L_A-1} \sigma_{u-j} - \beta \sum_{j=0}^{L_B-1} d_{u-j} = T_u - \sum_{j=0}^{L_A-1} \sigma_{u-j} - \beta \sum_{j=0}^{L_C-1} d_{u-j} \\ &= T_u - (1-\beta) \sum_{j=0}^{L_A-1} d_{u-j} - \beta \sum_{j=0}^{L_A-1} d_{u-L_B-j} + \beta \sum_{j=0}^{L_A-1} d_{u-L_B-L_C-j} - \beta \sum_{j=0}^{L_B-1} d_{u-j} \end{aligned} \tag{27}$$

The first part is related to the demand within period *u* and $u - (L_A - 1)$; Similarly, the second part is in between $u - L_B$ to $u - (L_A + L_B + L_C - 1)$; The third part is in between $u - (L_B + L_C)$ to $u - (L_A + L_B + L_C - 1)$; The Last part is for the range between *u* and $u - (L_B - 1)$. It is given that, $L_A \ll L_B$, i.e., the second and third parts do not conflict with the first and fourth parts of the equation. So, there will be no overlap during $L_A$ time period. By adding the first and fourth parts, we find, $-\sum_{j=0}^{L_A-1} \sigma_{u-j} - \beta \sum_{j=L_A}^{L_B-1} d_{u-j}$; Then, for the other two-part, $-\beta \sum_{j=0}^{L_A-1} d_{u-L_B-j} + \beta \sum_{j=L_A}^{L_A+L_C-1} d_{u-L_B-j}$. Net Stock Amplification ratio can be presented for two different scenarios as follows,

- $L_C < L_A$, i.e. lead time for manufacturing is relatively higher. So, $j_u = T_u - \sum_{j=0}^{L_A-1} d_{u-j} - \beta \sum_{j=L_A}^{L_B-1} d_{u-j} - \beta \sum_{j=0}^{L_C-1} d_{u-L_B-j} + \beta \sum_{j=L_A}^{L_A+L_C-1} d_{u-L_B-j}$. Then, the expected equation becomes.

$$NSA_r{}^{model-3} = \frac{\sigma_{j_u}^2}{\sigma_{d_u}^2} = \frac{L_A\sigma^2 + (L_B - L_A)\sigma^2\beta^2 + \sigma^2 L_C\beta^2 + \sigma^2 L_C\beta^2}{\sigma^2} = (1-\beta^2)L_A + \beta^2(L_B + 2L_C) \tag{28}$$

- $L_C \geq L_A$, i.e., the lead time for remanufacturing is higher or equal to the lead time to manufacture. So, it can be presented as, $j_u = T_u - \sum_{j=0}^{L_A-1} d_{u-j} - \beta \sum_{j=L_A}^{L_B-1} d_{u-j} - \beta \sum_{j=0}^{A-1} d_{u-L_B-j} + \beta \sum_{j=L_C}^{L_A+L_C-1} d_{u-L_B-j}$ . The overall expression will be as follows,

$$NSA_r{}^{model-3} = \frac{\sigma_{j_u}^2}{\sigma_{d_u}^2} = \frac{L_A\sigma^2 + (L_B - L_A)\sigma^2\beta^2 + \sigma^2 L_A\beta^2 + \sigma^2 L_A\beta^2}{\sigma^2} = (1-\beta^2)L_A + \beta^2(L_B + 2L_C) \tag{29}$$

The overall expression can be represented from Eq. (28) and Eq. (29) as, $NSA_r{}^{model-3} = (1-\beta^2)L_A + \beta^2(L_B + 2\min\{L_C, L_A\})$. Using $\min\{L_C, L_A\} = (L_C + L_A) - |L_A - L_C|$. Then,

$$NSA_r{}^{model-3} = L_A + \beta^2(L_B + L_C - |L_A - L_C| \tag{30}$$

### *5.4 Expressions for model-4*

Market pipeline visibility, manufacturing and remanufacturing are considered for this model. Here, $x_u - x_{u-1} = p_{u-1} - p_{u-L_A} + \beta(d_u - d_{u-L_B-L_C})$. Then, Eq. (12) yields,

$$p_u = (d_u - \beta d_{u-L_B-L_C}) - \beta(d_u - d_{u-L_B-L_C}) = (1-\beta)d_u \tag{31}$$

The Bullwhip ratio,

$$B_r{}^{model-3} = \frac{\sigma_{p_u}^2}{\sigma_{d_u}^2} = \frac{\sigma^2(1-\beta)^2}{\sigma^2} = (1-\beta)^2 \tag{32}$$

The inventory equation can be expressed as follows,

$$\begin{aligned} j_u &= T_u - \sum_{j=0}^{L_A-1} \sigma_{u-j} - \beta \sum_{j=0}^{L_B+L_C-1} d_{u-j} = T_u - (1-\beta)\sum_{j=0}^{L_A-1} \sigma_{u-j} - \beta \sum_{j=0}^{L_B+L_C-1} d_{u-j} \\ &= T_u - \sum_{j=0}^{L_A-1} d_{u-j} + \beta \sum_{j=0}^{L_A-1} d_{u-j} - \beta \sum_{j=0}^{L_B+L_C-1} d_{u-j} = T_u - \sum_{j=0}^{L_A-1} d_{u-j} - \beta \sum_{j=0}^{L_B+L_C-1} d_{u-j} \end{aligned} \tag{33}$$

Based on the conditions applied here, $T_u$Is fixed over the period. Then, $NSA_r$ becomes,

$$NSA_r{}^{model-3} = \frac{\sigma_{j_u}^2}{\sigma_{d_u}^2} = L_A + \beta^2(L_B + L_C - L_A) \tag{34}$$

**Table 2**

Bullwhip ratio and Net Stock Amplification ratio.

| Archetype No. | $B_r$ | $NSA_r$ |
|---|---|---|
| Model 1 | $(1+\beta^2)$ | $L_A + \beta^2 L_A$ |
| Model 2 | $(1+\beta^2)$ | $L_A + \beta^2 \lvert L_A - L_B \rvert$ |
| Model 3 | $(1-\beta)^2 + 2\beta^2$ | $L_A + \beta^2(L_B + L_C - \lvert L_A - L_B \rvert)$ |
| Model 4 | $(1-\beta)^2$ | $L_A + \beta^2(L_B + L_C - L_A)$ |

## 6. Result analysis

This analysis will investigate the relevant properties for all archetypes of the closed-loop supply chain systems. The smoothness of different operations and properties was determined using various indicators of the Bullwhip effect. In another section of the hybrid system, holding requirements and stockout occurrence will be related to some other properties.

The quantification of information transparency plays a vital role in deriving all the properties. We refer to the matrix related to market pipeline visibility with remanufacturing. If we define a range from '*a*' to '*b*' for the matrix, then '*a*' will express the metric for bullwhip effect or net stock amplification, and '*b*' will relate to remanufacturing (*Rem*) or market pipeline (*Mk*).

In this study, *I* = value of the information transparency, which can be measured from the difference between the supply chain performance with openness and without information transparency (Teunter et al., 2018; Author & Raghunathan, 2001). A similar approach for finding the value of the bullwhip ratio and net stock amplification ratio from the curve is the $\beta$ function value, adopted for the study. It will describe the different areas in that curve. The range of the curve will be $\beta \in [0,1]$. Since the return rate will vary over time, there are several chances to improve the result using the policies related to information sharing (Östlin et al., 2009), property-wise strategy setup and calculation based on the properties provided in the following sections.

### *6.1 Property-1*

The first property indicates the return rate's increased or decreased function value for the bullwhip ratio. It shows a U-shaped relationship, which is found based on information transparency. Table 2 revealed that the Bullwhip ratio is not connected to the lead time in all four archetypes. We can observe the same scenario for a traditional type of supply chain, which maintains the minimum value of mean square error (MMSE) and demand variability. The value of the bullwhip ratio is equal to 1 when the order-up-to related policy is found from the pass-on-orders policy (Ponte et al., 2019). In all four models, $B_r = 1$ and $\beta = 0$.

The value of the bullwhip ratio is highly connected to the value of the return rate. The relationship between the two is presented in Fig. 4. It shows that the bullwhip ratio for model 1 and model 2 is the same with the increase in the value of the return rate ($\beta$). This also answers one basic question related to a closed-loop supply chain system in contrast to the traditional system. For model 4, the value of the bullwhip ratio is decreased in a high ratio compared to the growth of the return rate. The resulting curve for model 3 shows a moderate relationship compared to the other three models, and it represents the U-shape relationship of the Bullwhip ratio concerning the return rate, which was also found in the research of Adenso-Díaz et al. (2012). So, the return rate will be reduced here with the slightly increasing value of the return rate, where the increment of the return rate in higher quantity shows the opposite result. Finally, for the value of return rate 1/3, the lowest amount of order visibility was found, which was 2/3.

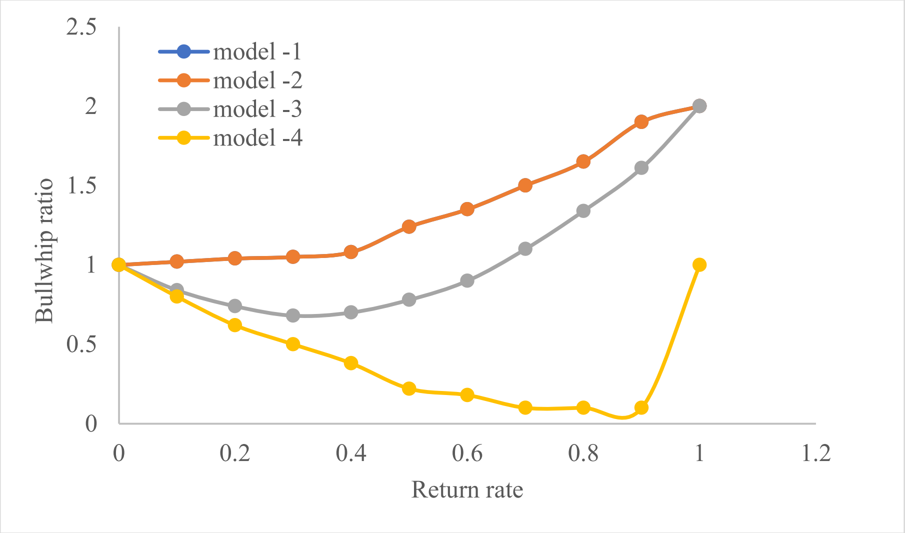

**Fig. 4.** Relationship of return rate with Bullwhip ratio

*6.2 Property-2*

Here, the visibility of the work-in-progress of the remanufacturer will be smoother compared to the previous closed-loop supply chain system. The manufacturer has access to check the visibility of the manufacturing processing and can use the information to rule out ordering a new product, as in model 2. This doesn't convert into a lower value of the Bullwhip ratio ($B_r$). Based on the scenario, there is a null opaque market, and the value of information transparency can be defined as follows,

$$I_{Rem}^{B_r} = \int_{\beta=0}^{\beta=1} \left({B_r}^1 - {B_r}^2\right) d\beta \; = \int_{\beta=0}^{\beta=1} ((1+\beta^2) - (1+\beta^2) d\beta = 0 \tag{35}$$

Serviceable stock dynamics can be improved using the additional information, enabling the customer requirements to be fulfilled cost-efficiently. The bullwhip effect will be reduced using the pipeline visibility of remanufacturing, and it will happen only when the manufacturer can ensure tracking of the product in the marketplaces. In Fig. 4, this scenario is represented by a curve found for model 3 and model 4. The reduction in the value of the return rate is $\beta < 1/3$,, Which is relatively low, i.e., the convex curve for minimum Bullwhip ratio value in model 3. From this point, the difference increased. The information on the remanufacturing pipeline can be found in the transparent market pipeline and is represented as follows,

$$I_{Rem}^{B_r} = \int_{\beta=0}^{\beta=1} \left({B_r}^3 - {B_r}^4\right) d\beta \; = \int_{\beta=0}^{\beta=1} ((1-\beta)^2 + 2\beta^2 - (1-\beta)^2) d\beta = 2/3 \tag{36}$$

To enable visibility for the remanufacturing end, a significant reduction in the average value can be confirmed by this part.

*6.3 Property-3*

Here, it shows that market visibility ensures the reduction in the Bullwhip ratio. Market pipeline visibility will be used to reduce the Bullwhip effect ratio. If information on the pipeline for remanufacturing can be ensured, market transparency value will be higher. Importantly, for model 1 and model 2, transparency of the market pipeline was not enabled. So, demand should be amplified in a closed-loop system. For this reason, ${B_r}^{model-1} = {B_r}^{model-2} > 1, \forall\, \beta > 0$. For the opaque case, the remanufacturer's pipeline is not accessible. Incorporating the market information will eliminate the Bullwhip effect if the chain has a high return rate. ${B_r}^{model-3}$ >1, $\forall\, \beta > 2/3$. For this scenario, the value of information transparency can be determined as follows,

$$I_m^{B_r} = \int_{\beta=0}^{\beta=1} \left({B_r}^1 - {B_r}^3\right) d\beta = \int_{\beta=0}^{\beta=1} (1+\beta^2) - 2\beta^2 - (1-\beta)^2) d\beta = 1/3 \tag{37}$$

The assessment of the market information will remove the Bullwhip effect from the closed-loop supply chain. This is for the transparent scenario. So, ${B_r}^{model-4} < 1, \forall\, \beta > 0$. Now, it can be obtained that,

$$I_m^{B_r} = \int_{\beta=0}^{\beta=1} \left({B_r}^2 - {B_r}^4\right) d\beta = \int_{\beta=0}^{\beta=1} (1+\beta^2) - (1-\beta)^2) d\beta = 1 \tag{38}$$

For the remanufacturing site, when there is transparency of the information, the value of the visibility of the market will be higher.

### *6.4 Property-4*

The variability of net stock in a closed-loop supply chain is higher than that of the traditional supply chain. Thus, relatively less performance for the closed-loop supply chain will be achieved. Considering the lead time related to consumption, the positive value of the lead times will be the highest. i.e. $L_A$, $L_B$, $L_C > 0$ and $L_C \gg L_A$, $L_B$. The basic properties of the related function will be demonstrated later. The value of the first derivative is 0, which is calculated concerning $\beta$. Then, the value of their second derivative is positive in all cases. This will not be applicable only when $L_A \gg L_B$ in model 4. Based on this scenario, increasing the net stock amplification ratio value will reduce the bullwhip ratio for a closed-loop supply chain. $\beta = 0$ and $NSA_r = L_A$ explains the traditional system of the order-up-to policy. This concludes that the value of the bullwhip ratio is decreased in the context of a closed-loop supply chain network structure, which increases the net stock amplification ratio (Turrisi et al., 2013). It is quite interesting that the value of the Bullwhip effect only depends on the value of the return rate. Sequentially, $NSA_r$ relies on the value of lead times. $L_A$, $L_B$ and $L_C$ for the model 4, while model 1 is connected to $L_A$ and $L_B$, $L_C$ for model 2.

### *6.5 Property-5*

Remanufacturing pipeline variability will reduce the net stock variability. This will not apply only if the lead time related to remanufacturing is higher than that of the manufacturing. When the market pipeline is opaque, the reduced value of $NSA_r$ will be provoked to enable the work-in-progress of the remanufacturer. i.e. ${NSA_r}^{model-1} - {NSA_r}^{model-2} = {NSA_r}^{model-3} - {NSA_r}^{model-4} = \beta^2(L_A - |L_A - L_C|)$. It was observed that, for $L_A \geq L_C$ presents the most important common scenario of the closed-loop supply chain. For this case analysis, ${NSA_r}^{model-1} - {NSA_r}^{model-2} = {NSA_r}^{model-3} - {NSA_r}^{model-4} = \beta^2 \mathrm{L_C}$. Higher value of $L_C$ will highly reduce the value of $NSA_r$. But the conclusion will be different for the reverse scenario, i.e. $L_A < L_C$. So, ${NSA_r}^{model-1} - {NSA_r}^{model-2} = {NSA_r}^{model-3} - {NSA_r}^{model-4} = \beta^2(2L_A - L_C)$. Transparency will reduce the value of the pipeline of remanufacturing for $L_A < L_C < 2L_A$. If, $L_C > 2L_A$, No benefit or loss. The highest reduction will be achieved when $L_C = L_A$. The value of the information transparency can be written as follows,

$$I_{Rem}^{NSA_r} = \int_{\beta=0}^{\beta=1} \left({NSA_r}^1 - {NSA_r}^2\right) d\beta = \int_{\beta=0}^{\beta=1} \left({NSA_r}^3 - {NSA_r}^4\right) d\beta \tag{39}$$

$$= \int_{\beta=0}^{\beta=1} \beta^2(\mathrm{L_A} - |\mathrm{L_A} - \mathrm{L_C}|\ d\beta = \frac{\mathrm{L_A}}{3} - \frac{|\mathrm{L_A} - \mathrm{L_C}|}{3}$$

Here, for Eq. (39),

For $\mathrm{L_A} \geq \mathrm{L_C}$ , $I_{Rem}^{NSA_r} = \frac{\mathrm{L_C}}{3}$

For $\mathrm{L_A} < \mathrm{L_C}$ , $I_{Rem}^{NSA_r} = \frac{2\mathrm{L_A} - \mathrm{L_C}}{3}$

For $\mathrm{L_C} > 2\mathrm{L_A}$ , $I_{Rem}^{NSA_r}$ = negative

Fig. 5 to Fig. 7 illustrate the relationship between the net stock amplification ratio and return rate for different lead time values. The first case shows that the market system's transparent and opaque pipeline will benefit from the visibility of the pipeline for remanufacturing. Maximum information sharing is achieved when the lead time for manufacturing and remanufacturing is equal. Lastly, a negative value for both cases of information transparency is achieved.

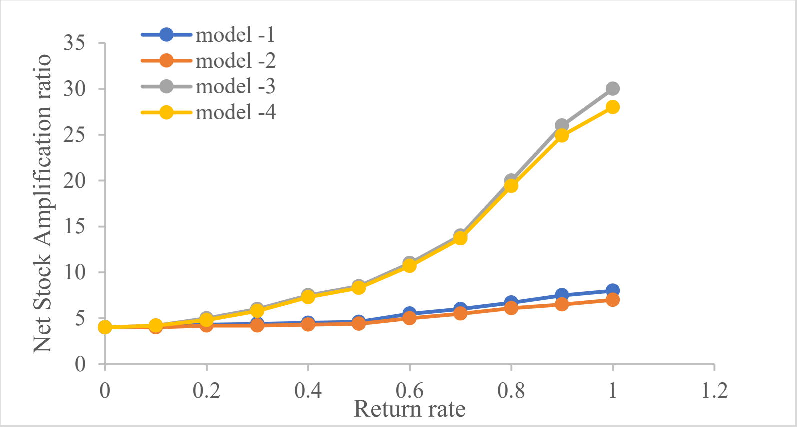

**Fig. 5.** Relationship of Net Stock Amplification ratio with return rate ($L_A = 4$, $L_B = 20$ and $L_C = 2$)

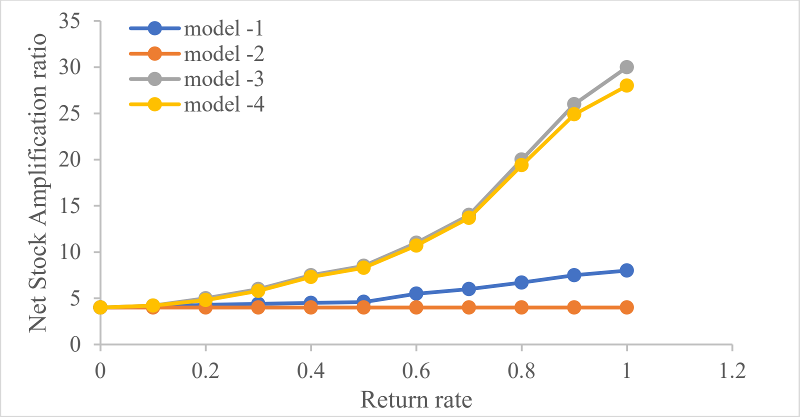

**Fig. 6.** Relationship of Net Stock Amplification ratio with return rate ($L_A = 4$, $L_B = 20$ and $L_C = 4$)

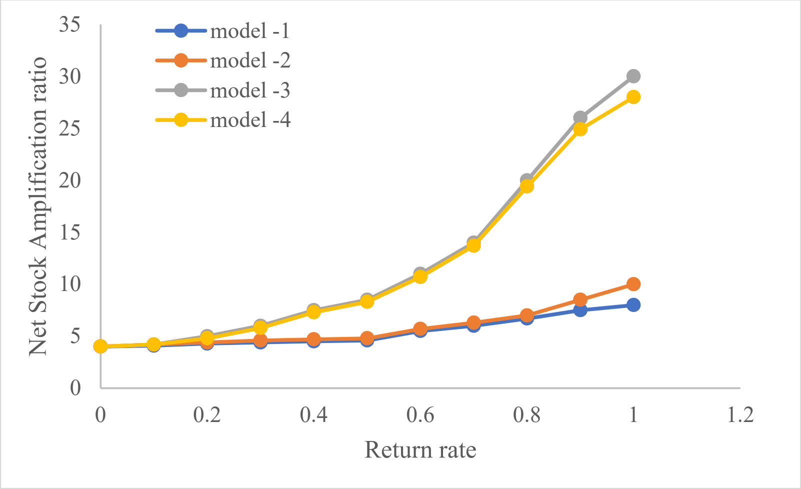

**Fig. 7.** Relationship of Net Stock Amplification ratio with return rate ($L_A = 4$, $L_B = 20$ and $L_C = 10$)

*6.6 Property-6*

Here, the variance of the net stock is increased using the information from the market pipeline. So, the trade-off between the holding cost and the expected service level will create a negative impact. The main reason for increasing the value of the amplification ratio is the higher lead time for consumption. The effect of market data on that ratio is the same as pipeline visibility for remanufacturing. So, ${NSA_r}^{model-1} - {NSA_r}^{model-3} = {NSA_r}^{model-2} - {NSA_r}^{model-4} = \beta^2(L_A + |L_A - L_C|) - L_B - L_C)$. The value of information transparency for this ratio can be presented as follows,

$$I_m^{NSA_r} = \int_{\beta=0}^{\beta=1} \left(NSA_r{}^1 - NSA_r{}^3\right) d\beta = \int_{\beta=0}^{\beta=1} \left(NSA_r{}^2 - NSA_r{}^4\right) d\beta$$
$$= \int_{\beta=0}^{\beta=1} \beta^2 (\mathrm{L_A} + |\mathrm{L_A} - \mathrm{L_C}|) - \mathrm{L_B} - \mathrm{L_C})\ d\beta = \frac{|\mathrm{L_A} - \mathrm{L_C}| + \mathrm{L_A} - \mathrm{L}_B - \mathrm{L_C}}{3} \tag{40}$$

Here, for Eq. (39),

For $\mathrm{L_A} \leq \mathrm{L_C}$ , $I_m^{NSA_r} = \frac{-\mathrm{L_C}}{3}$

For $\mathrm{L_A} > \mathrm{L_C}$ , $I_m^{NSA_r} = \{2(\mathrm{L_A} - \mathrm{L_C}) - \mathrm{L}_B\}/3$

For $\mathrm{L_C} > 0$ , $I_m^{NSA_r}$ = negative

For $\mathrm{L_B} \gg \mathrm{L_A}$ , $I_m^{NSA_r}$ = negative

*6.7 Property-7*

The paradox of lead time will manifest itself in the closed-loop supply chains, and information transparency and inventory variability will help to show that Fig. 8 represents the relationship between the net amplification ratio and the remanufacturing lead time.

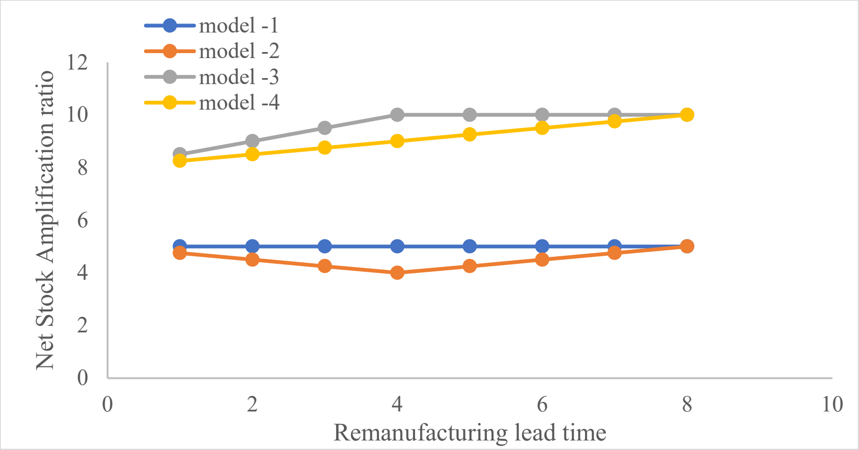

**Fig. 8.** Relationship of net stock amplification ratio with remanufacturing lead time.

For model 1, it is shown that the amplification ratio is not dependent on the value of $L_C$. It expresses that the paradox of the lead time is not connected to the system's transparency. In model 4, the net amplification ratio will be increased with the increment of the value of remanufacturing lead time. For this reason, it can be concluded that the reduced value of $L_C$ helps to improve the system's dynamics. In model 3, reducing the value of $L_C$ makes smoother inventory dynamics. However, the variability of net stock has no impact on the decrease of $L_C$. A straightforward effect was found for the lead time for manufacturing in four models. This clarifies that understanding the lead time-related dynamics is an important tool to minimise the investment, which is unnecessary for the closed-loop supply chain system.

## 7. An Economic study's variability trade-off

For modelling the variability trade-off for the system, production cost related to capacity connected with an unstable schedule for production was assumed here. This is related linearly to the order variance, $\sigma_p^2$. Then, the unit cost is denoted by, $k_p$. It was also assumed that the stock-out and holding costs were inventory-related. They are related linearly to the inventory variance, $\sigma_i^2$. For this case, the unit cost is denoted by $k_i$. Note that, $k_p, k_i \geq 0$, where $k_p, k_i$ is the value of product unit (*pu*). The monetary unit is expressed by (*mu*). For the analysis of variability trade-off, the approach has an objective function which is common in traditional supply chains, which is presented as follows, $K = k_p\sigma_p^2 + k_i\sigma_i^2$ (Disney et al., 2004). From the definition of the matrix, an equation can be found as, $\sigma_p^2 = \sigma^2 B_r$ and $\sigma_p^2 = \sigma^2 NSA_r$ expresses the objective function based on cost, which depends on the bullwhip and net stock amplification ratios. It was found from different literature that new products incurred (40-60) % higher costs than remanufactured products (Cannella et al., 2016). Unit cost $k_s$ represents the fixed cost between manufacturing and remanufacturing. To save the price of the remanufactured product, $k_s > 0$. Similarly, $k_s < 0$ for the extra cost of the remanufactured product. So, the objective function can be represented as follows,

$$K_{clsc} = k_p\sigma_p^2 B_r + k_i\sigma_i^2 NSA_r - k_s\beta\mu \tag{41}$$

Dividing the Eq. (41) by the demand value (mean) i.e. $\mu$ leads toward $K^d_{clsc} = \frac{k_{clsc}}{\mu} = k^d_p B_r + k^d_j NSA_r{-}k_s\beta$. Grouping of the economic parameters is essential for finding the value of the dispersion index as, $\delta = \sigma^2/\mu$. The uncontrollable characteristics of our system were considered in this study. It can be defined that, $k^d_p = k_p\delta$ and $k^d_j = k_j\delta$, both in the value of *mu/pu*, leads to the objective function as follows,

$$K^d_{clsc} = k^d_p B_r + k^d_j NSA_r{-}k_s\beta \tag{42}$$

Here, $K^d_{clsc}$ is used to focus on three different sources that correlate with the cost and depend on the return rate. It should be noted that the cost related to sharing information is not considered here. The Eq. (42) represents the four archetypes for this research work. Deeper understanding of optimal return rate, $\beta^*$, it will be discussed in the convex matrix.

For model 1, using the expression presented in Table 2, Eq. (42) leads to $K^d_{clsc} = k^d_p(1+\beta^2)\ k^d_j(L_A+\beta^2 L_A) - k_s\beta$, its first derivative equals zero, leads to the new equation, which is minimised for,

$$\beta^*_{model-1} = \frac{k_s}{2(k^d_p + k^d_j L_A)} \tag{43}$$

Eq. (43) is a cost-based objective function where the return rate value is constrained to the interval [0,1]. The return rate should be taken from the economic perspective. It proves that the return volume in model 1 of the closed-loop supply chain is optimal based on cost. A conclusion can be drawn as follows,

1. For $k_s \le 0$, the value of the return rate $\beta$, it should be 0.
2. For larger weighted sum of others cost $k_s$, $k_s \ge 2\left(k^d_p + k^d_j L_A\right)$, the value of return rate $\beta$ should be 1.
3. For $0 < k_s < 2\left(k^d_p + k^d_j L_A\right)$, the value of the return rate $\beta$ should be in between 0 and 1.

For model 2, using the expression presented in Table 2, Eq. (42) leads to $K^d_{clsc} = k^d_p(1+\beta^2) + k^d_j(L_A + \beta^2|\mathrm{L_A} - \mathrm{L_C}|) - k_s\beta$, its first derivative equals zero, leads to the new equation which is minimised for,

$$\beta^*_{model-2} = \frac{k_s}{2(k^d_p + k^d_j|\mathrm{L_A} - \mathrm{L_C}|)} \tag{44}$$

For Eq. (44), will it be possible to remanufacture efficiently when $\beta^*_{model-2} > 0$.

For model 3, using the expression presented in Table 2, Eq. (42) leads to $K^d_{clsc} = k^d_p((1-\beta)^2 + 2\beta^2) + k^d_j(L_A + \beta^2(\mathrm{L_B} + \mathrm{L_C} - |\mathrm{L_A} - \mathrm{L_C}|)) - k_s\beta$, its first derivative equals zero, leads to the new equation, which is minimised for,

$$\beta^*_{model-3} = \frac{k_s}{2(3k^d_p + k^d_j(\mathrm{L_B} + \mathrm{L_C} - |\mathrm{L_A} - \mathrm{L_C}|))} \tag{45}$$

For model 4, using the expression presented in Table 2, Eq. (42) leads to $K^d_{clsc} = k^d_p((1-\beta)^2 + 2\beta^2) + k^d_j(L_A + \beta^2(\mathrm{L_B} + \mathrm{L_C} - \mathrm{L_A})) - k_s\beta$, its first derivative equals zero, leads to the new equation, which is minimised for,

$$\beta^*_{model-4} = \frac{k_s}{2(k^d_p + k^d_j(\mathrm{L_B} + \mathrm{L_C} - \mathrm{L_A}))} \tag{46}$$

The expression structure of the optimal return rate for model 4 is similar to the equation of model 3, which is rational for remanufacturing. Here, the conditions for ensuring economic variability are $k_s > 0$ and $k_s \ge 2(\mathrm{L_B} + \mathrm{L_C} - \mathrm{L_A})k^d_j$. The economic target should be $\beta = 1$.

*7.1 Cost calculations with numerical example*

For the illustration of the previous analysis, a numerical example is considered. For the simplification, it was assumed that $k^d_p = 1\frac{mu}{pu}, k^d_j = 1\frac{mu}{pu}$. The values of three lead times were considered as, $\mathrm{L_A} = 4$, $\mathrm{L_B} = 20$ and $\mathrm{L_C} = 2$. The matrix indicator $K^d_{clsc}$, expresses the cost related to operations concerning the return rate, $\beta$, for all the scenarios where the value of $k_s$ is different in the closed-loop supply chain system.

- Scenario-1: The manufacturing cost is the same as the remanufacturing cost. The product used in remanufacturing does not create any extra benefit here compared to the traditional manufacturing system. Fig. 9 is used to illustrate the scenario, $k_s = 0$.

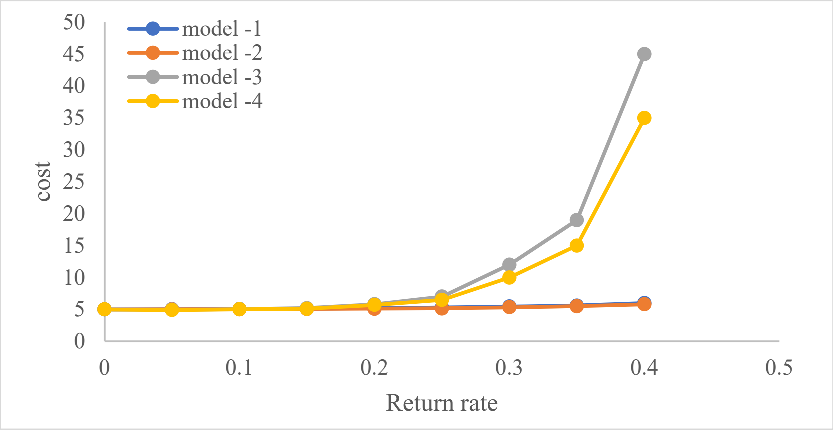

**Fig. 9.** Relationship of return rate with cost (scenario-1, $k_s = 0$)

- Scenario-2: This representation expresses the practical scenario in terms of cost. Manufacturing costs are significantly higher than those of remanufacturing. However, the cost difference is the same as other costs in the closed-loop supply chain system. In this case, $k_s = 1$ and it is illustrated in Fig. 10.

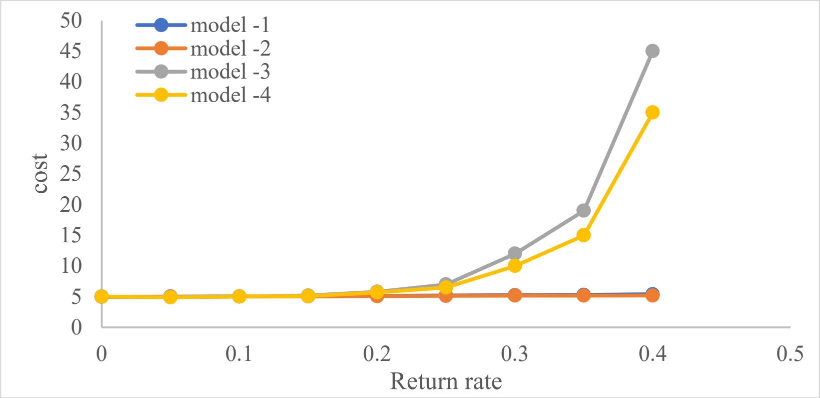

**Fig. 10.** Relationship of return rate with cost (scenario-2, $k_s = 1$)

- Scenario-3: The difference between costs related to manufacturing and remanufacturing is significantly higher than that of the previous scenario. Here, $k_s = 9$ and it is illustrated in Fig. 11.

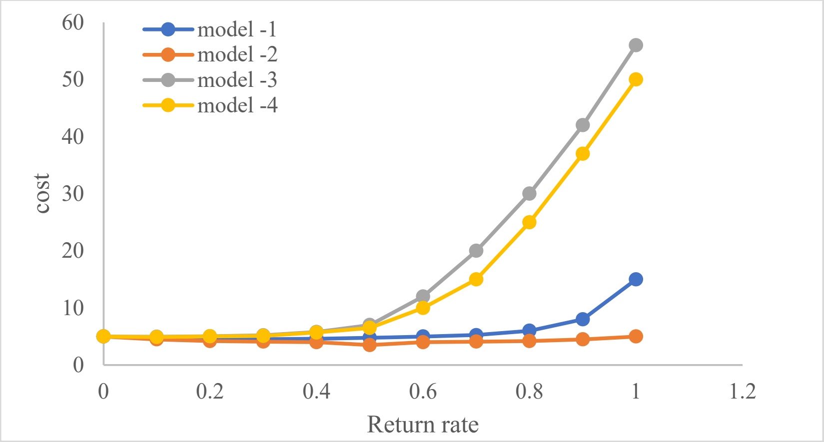

**Fig. 11.** Relationship of return rate with cost (scenario-3, $k_s = 3$)

- Scenario-4: The remanufacturing cost is significantly smaller than the manufacturing-related cost. This concludes that the economic stability for remanufacturing is higher. In this scenario, $k_s = 9$ and it is illustrated in Fig. 12.

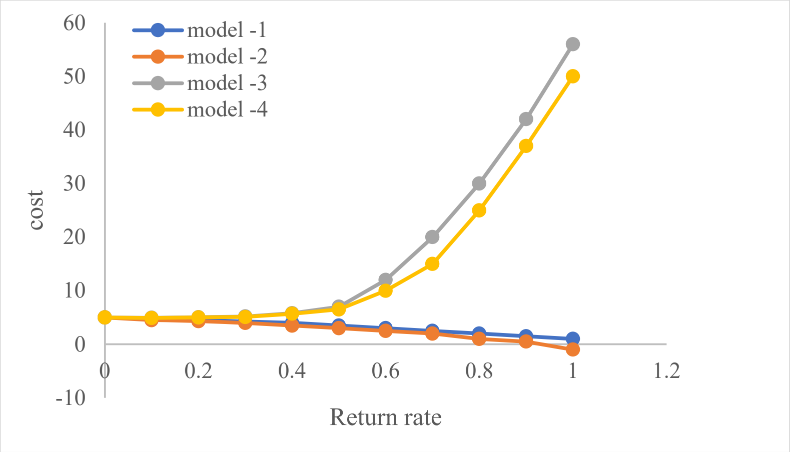

**Fig. 12.** Relationship of return rate with cost (scenario-4, $k_s = 9$)

## 8. Discussion

Several findings can be derived from the result analysis part. The cost generated in a closed-loop supply chain is represented by Fig. 9. From the conclusion of the previous discussion, it can be declared that the optimal return rate for model 1 and model 2 is 0. For this reason, there is no need to remanufacture the product for these models. It is given that it does not directly affect the savings from the comparison with manufacturing. Then, it will not improve the closed-loop supply chain's system dynamics. However, the value of $k_s = 0$ in model-3 and model-4. The hybrid system ensures a slight benefit from remanufacturing a small quantity of the products. The optimal return rate value for model 4 is 5.32%. It is analytically shown that the remanufactured product is slightly more expensive, where $k_s < 0$, and it is only for model 3 and model 4. Here, a higher bullwhip ratio value will be achieved to increase the value of the return rate. In the second scenario, the four curves' optimal return rate value lies between intervals [0,1]. Minimum cost is achieved for the return rate presented in Fig. 10. The optimal return rate value for model 2 is 16%. For model 4, the value is 7.92%. A higher return rate is found for a higher net stock amplification ratio value. From the previous analysis, for all archetypes, the value of the optimal return rate is increased with the increasing value of the parameter, $k_s$. The savings related to remanufacturing are higher than those of other companies. From the curves of Fig. 11, the value of optimal return for model 2 is the highest, i.e. 50%, whereas the rate for model 4 is only increased to 13%. The value of the optimal return rates for model 3 and model 4 is increased with the increasing net stock amplification ratio values in those models. It can be concluded that, for this scenario, strong cost reductions when comparing traditional open-loop supply chains are found for the closed-loop chains. Finally, the cost structure of the closed-loop supply chain of model 4 is illustrated in Fig. 12. It illustrated that; k sub s is $k_s \gg k_p^d, k_j^d$. The optimal value for return rate is 1. This case happened only for model 3. The representation of the model can be summarised as, $\beta^*_{model-2} > \beta^*_{model-1} > \beta^*_{model-4} > \beta^*_{model-3}$ for the moderately higher value of $k_s$. Similarly, the sequence for a lower value of $k_s$ is $\beta^*_{model-4} > \beta^*_{model-3} > \beta^*_{model-2} > \beta^*_{model-1}$. From this discussion, it is clear that model 4 can minimise the costs associated with a closed-loop supply chain for the low and moderate type values of $k_s$.However, for the higher parameter value $k_s$, model 2 gives the lower costs. The cost of information sharing was not considered here.

## 9. Conclusion

This research investigated the dynamics and performance of the closed-loop supply chain network system, highlighting the Bullwhip effect. The metrics of the Bullwhip ratio and net stock amplification ratio were used to measure the order and inventory-related variability. Quantification of the return rate and lead time associated with relevant fields for four archetypes of the system of manufacturing-remanufacturing was investigated here in this research study. This can be distinguished by the degree of the visibility of information. An efficient system based on the requirements considering the stock-out scenario was also considered, and findings from the latest research papers were considered. The smoothness of the order variability greatly impacts the return value. It was shown that the impact may be positive or negative based on the scenario. By exploring four archetypes, it was found that both the variability in order and inventory found a positive impact from the increment of the remanufacturing pipeline transparency. Some exceptions were found, and they were discussed in the earlier sections. Additionally, it was revealed that market pipeline visibility decreases the variability of orders with increased inventory. The information transparency value is the same regardless of remanufacturing pipeline visibility. However, the information transparency value in the remanufacturing pipeline depends on the available information in the market pipeline. Based on our assumption, the bullwhip ratio does not depend on lead time. Inventory-related variability is strongly affected by lead time. Lead time also affects the degree of transparency of information. This research finds that the paradox documented previously for the lead time of remanufacturing will not emerge depending on the available information transparency. This work also demonstrated the implication of optimal return rate for four archetypes, which rely on the supply chain cost structure, lead time and customer demand variability. The supply chain may benefit from the remanufactured product collected from the market, and it was also done for that product, which is more expensive than manufacturing the new one. It was shown by using the relationship of another factor with cost.

## 10. Limitations and future scope

The order-up-to policy was used in this study to manage the serviceable inventory, where the push-type supply chain model was considered for recoverable inventory. This research is partially limited to MMSE forecasting and demand. Future research can use better implications of demand characteristics and forecasting models. The relationship between the demand and the return process can be performed in future works. The deterministic value of lead time and the return rate was considered here. So, their value was uncertain in some settings. It can be improved in the next extension of this research. This work does not incorporate the costs associated with transparency of information. So, improved work can be performed by bringing them into consideration. Interaction among all the relevant parameters was not performed in detail. It can be included in future research. Pure remanufacturing-related systems with real-time problem-solving analysis can be performed to implement the closed-loop supply chain network system effectively.

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