Towards sustainable net-zero buyer-supplier relationship: An approach to quantify green bullwhip effect

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Abstract

Our paper presents a comprehensive study on sustainable supply chain management, focusing on the "green bullwhip effect" and its implications for net-zero buyer-supplier relationships. It attempts a novel approach to quantify the impact of environmental regulations on supply chain dynamics, particularly through the lens of Production and Inventory Control Systems (PICS) under Perceived Emission Rate (PER) feedback. Classical bullwhip effect, where small disturbances in demand can amplify through the supply chain, leading to inefficiencies and increased costs. A ripple effect from the change in environmental effect termed green bullwhip is observed. This study explores the green bullwhip effect by integrating environmental requirements into a buyer-supplier relationship through PICS under PER feedback. Our work also delves into the Vendor-Managed Inventory (VMI) concept and its potential to improve supply chain performance by enhancing coordination among echelons. It suggests that a Vendor-Managed Production and Inventory Control System (VM-PICS) under emission feedback could be a viable solution for managing the green bullwhip effect. Emphasized on the importance of collaborative approaches in achieving sustainable supply chain management and the role of VM-PICS in facilitating environmentally responsible practices. In conclusion, the paper calls for further research to develop simulation-based models that can quantify the green bullwhip effect and offer strategies for its mitigation.

Keywords: PICS, Emission Permit, Green Bullwhip, Vendor-Managed Inventory, Perceived Emission Rate, Ripple Effect, VM-PICS

1. Introduction

Sustainability has become a paramount consideration in the contemporary supply chain management landscape. Integrating environmental considerations into the supply chain has given rise to a Green Supply Chain Management (GSCM). With an endeavour to mitigate the environmental footprint of operations while ensuring economic viability, broadly categories GSCM practices. However, the prevailing research indicates that GSCM's environmental focus may overshadow other sustainability facets, such as economic viability and social equity, suggesting a need for a more balanced approach (Seuring and Müller, 2008). This paper introduces the concept of Production and Inventory Control Systems (PICS) under Perceived Emission Rate (PER) feedback proposed by Deval and Venkateswaran (2022a). Under this methodology, attempts to maintain inventory and supply lines from operations within systems' emissions restrictions are explored. By dynamically adjusting parameters, PICS under PER feedback ensures real-time compliance with emission standards, thereby reducing the emission footprint of production systems. This approach aligns with environmental regulations, compelling production systems to adhere to individual echelon restrictions and, in turn, influencing overall system performance.

Despite the promise of PICS under PER feedback, challenges persist. Operating under bounded rationality, individual echelons may inadvertently contribute to unsustainable supply chain management (Sterman, 2010). A significant knowledge gap remains concerning the short-term impact of sustainability considerations on system performance. This gap is particularly critical in supply chain management, characterized by the complex interplay of multiple players with nearly identical operations, who must collaborate to foster sustained growth of both individual subsystems and the overall supply chain. The paper posits an essential question: How does a change in environmental requirements at an individual echelon affect the supply chain? Addressing this query is vital for understanding the broader implications of sustainability initiatives within supply chains.

This introduction sets the stage for a detailed exploration of sustainable net-zero buyer-supplier relationships and the quantification of the green bullwhip effect (Lee et al., 2014; Seles et al., 2016). A classical bullwhip is part of the operation due to varying end-customer demand with information distortion; a high-order variability by individual echelons is passed from downstream to upstream echelons (Lee et al., 1997; Disney and Towill, 2003b). Usually, mitigation strategy includes vendor-managed inventory (VMI), electronic Point-of-Sale (POS) sharing, better forecasting methodology, etc (Disney et al., 2013). Observed as customer-driven for short-term fluctuations, a similar phenomenon is observed as a ripple effect in the supply chain where structural change or varying parameters have a propagation impact on upstream echelons (Dolgui et al., 2018). An event-driven change in environmental requirements introduces a green bullwhip, where environmental pressure for an individual echelon propagates as pressure is passed downstream to upstream echelon (Lee et al., 2014). A sustainability challenge is ensuring operations' economic viability for given environmental restrictions along with environmental pressure from the downstream echelon (Seuring and Müller, 2008). This paper encapsulates the criticality of balancing environmental concerns with economic and social sustainability in supply chain management by attempting to introduce the notion of vendor-managed production and inventory control system under perceived emission rate to explore mitigation strategy for green bullwhip.

2. Literature Review

Automatic Pipeline Inventory Order-based Production Control System (APIOBPCS) as a push system, is driven by Customer Demand (CD), an exogenous variable; thus, a loss to the system is compensated by a decision variable for orders, Production Release (PREL). As a decision variable, PREL comprises forecasted demand and adjustments to both pipeline and inventory. A decision maker needs to decide between two conflicting objectives: (1) a rapid inventory recovery and (2) a reduction of demand amplification called Bullwhip (Lin et al., 2017). It uses three control parameters: the smoothing rate for forecasting demand, pipeline adjustment rate, and inventory adjustment rate to adjust system recovery. Note that APIOBPCS is reduced to the IOBPCS model if no pipeline adjustment and fixed desired inventory are accounted for in the PREL decision. Deziel and Eilon (1967) studied a linear production control system for a specific configuration with an equal adjustment rate to pipeline and inventory known as DE-line. Interestingly, the DE control setup ensures the system's stability and robustness against any system's non-linearity (Disney and Towill, 2003b).

APIOBPCS is well-documented in the academic literature, varying from the study of stability, system performance, optimization, and information sharing strategy for collaboration among multi-player systems. Control parameter selection (Disney and Towill 2002, Riddalls and Bennett 2002, Warburton et al. 2004, Disney et al. 2006a,b, Venkateswaran and Son 2007) impact stability in both continuous and discrete time domains and helps to avoid undesired system havoc. Further, prevailing literature also investigates system performance for cost, bullwhip effect, inventory variance, and service level (Dejonckheere et al. 2003, Disney and Grubbström 2004, Villegas and Smith 2006, Disney et al. 2006a, Chen and Disney 2007, Cannella and Ciancimino 2010, Bijulal et al. 2011).

Sterman (1988) defined a Stock Management Structure (SMS) to study the influence of information distortion in a vertical supply chain for a Beer Game using a serially linked stock management structure. Sterman (2010) refers to a supply chain as a cascade of firms, each receiving orders from the downstream echelon and adjusting production/inventory and production capacity to meet their requirements. Each supply chain echelon maintains its inventory and production processes based on aggregate functionality. Therefore, a cascade of AP(V)IOBPCS or Stock Management Structure better represents information and material flow in a vertical supply chain. The literature above (except Sterman, 2010) assumes individual/multiple echelons of a supply chain with linear feedback.

2.1. Production and Inventory Control System (PER) under Perceived Emission Feedback (PER)

Consider a two-tier Production and Inventory Control System (PICS) under Perceived Emission Rate (PER) proposed by Deval and Venkateswaran (2022a) where orders are adjusted to ensure emission compliance for two-echelon vertical supply chain representation. At an individual level for each echelon, two classical decisions about "*How much to order?*" and "*How much to store?*" (Disney and Towill, 2003c) along with "*How much to Emission Adjusted Orders?*" for environmental compliance are explored. Three key stocks, namely, *supply line* (or *work in process*); *inventory* and *perceived emission rate (PER)* are to be maintained as per desired level using adjustment rate known as control parameters. For more details, refer to figure 1 with solid links representing classical feedback and dashed denoting PER feedback. Balancing loop: B1 and B2, which adjusts the discrepancy between the desired level of Work-in-Process and Inventory against the actual level. Additional feedback from balancing loop B3 is based on the discrepancy between PER and available EP adjust order (PREL) to reduce system emission. A classical PICS is driven by the customer demand which is exogenous to system, but under this specific setup emission permit (EP) along with customer demand drive operations. Three balancing loops, along with delay, are an inherent structure for oscillations in such a system. A widely acceptable industrial policy, Order-upto (OUT), is used to adjust the supply line and inventory discrepancy to ensure the stability of the classical system (Disney et al., 2008). A further extension of the system under PER feedback is explored by (Deval and Venkateswaran, 2022b) for stability under emission control parameters.

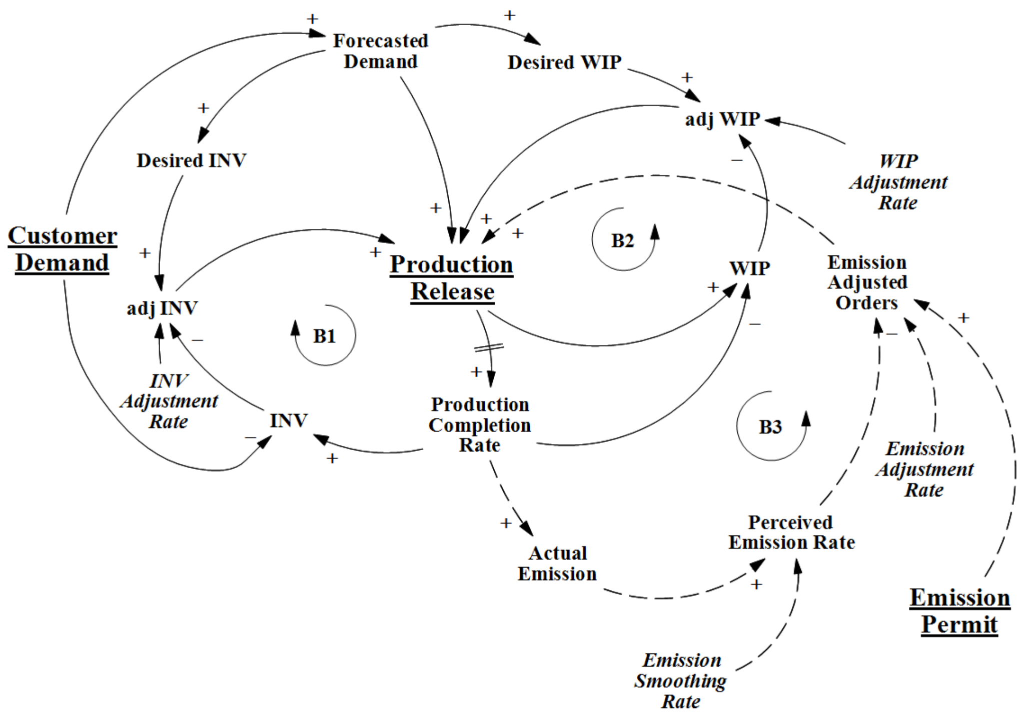

Figure 1: Individual echelon for Production and Inventory Control System (PICS) under Perceived Emission Rate (PER) Feedback

2.2. *Supply Chain Management: A Cascade of PICS*

Supply Chain Management (SCM) ensures smooth operations from extracting raw materials to disposing-off consumed products towards end-of-life. With each echelon defined for a specific role, coordination among echelons results in better supply chain performance (Chopra et al., 2007). Under a traditional setup, each echelon bases its production or delivery orders on its respective customer sales. Such a structure involves decision support to solve "just how much to order the production system to enable a supply chain echelon to satisfy its customers' demands" (Disney and Towill, 2003a). Since information about demand is only limited to immediate customers, each echelon is responsible for individual production and inventory management. This lack of visibility in real-time demand causes undesired havoc to the supply chain, which cannot be eliminated, but mitigation opportunities can be explored (Lee et al., 1997). Production and Inventory Control System (PICS) aims to transform incomplete information about the marketplace into coordinated plans for producing and replenishing raw materials into the system (Axsäter, 2015) for each echelon.

A typical supply chain structure consists of cascades of firms (or echelons) receiving orders and adjusting production and production capacity to meet system requirements (Sterman, 2010). Material flow from upstream to downstream against an information flow from downstream to upstream requires due consideration in decision-making (Lee et al., 1997). With each echelon maintaining a respective inventory of material and finished goods, a small disturbance from downstream amplifies orders for upstream (Forrester, 1997). From a generic stock management structure, Sterman (2010) points out that the different complexities of feedback in supply chain inventory and the pressure of time and resource constraints lead to irrational decisions. Empirical studies have also identified demand signal processing, non-zero lead time, price variations, rationing and gaming, and order batching sources of demand amplification as relevant contributors to the "Bullwhip Effect" (Lee et al., 1997). With limited (distorted) information about demand, the traditional structure above introduces instability into a multi-echelon setup. Due to money-hemorrhaging sources from holding and backlog charges, production ramp-up/down costs, etc., the bullwhip effect becomes necessary to mitigate (McCullen and Towill, 2001).

To improve operational efficiencies in supply chain operations, each echelon must comply with cooperation by sharing demand and inventory information with suppliers and customers. As per Disney and Towill (2002) in a Vendor Managed Inventory (VMI), the distributor shares information and/or point of sales data rather than orders with the Manufacturer. A manufacturer can net off the inventory from delivery and sales if the distributor cannot share inventory information but shares end sales data electronically. Under the classical setup of VMI, distributor, and manufacturer as buyer-supplier coordination among two-tier helps to determine a negotiated re-order point to ensure adequate Customer Service Levels (CSLs). Thus, a manufacturer is responsible for the distributor's inventory management to ensure high availability. When inventory is below the re-order point, a shipment from the manufacturer replenishes the distributor's inventory position.

Traditional vendor-managed inventory (VMI) focuses on improving the relationship between buyer and supplier. Dynamically, the buyer shares inventory and sales information with the retailer to improve customer service level (CSL). As per mutual agreement, the buyer determines a re-order point, and based on shared information, the supplier also manages the buyer's inventory. Under VMI setup, allocation of responsibility and agreed target setting play a significant role (Disney and Towill, 2003c). As per Disney and Towill (2003c), actual inventory at buyer is compared with negotiated in the buyer-supplier relationship. Without building up excessive inventory in a collaborative framework, order replenishment is triggered with buyers' customer demand. With the dynamic requirements of buyers', the forecast is updated regularly to ensure high CSL. Disney (2001) provides all essential support to determine re-order points. A CSL and stock trade-off is determined by netting off the good in-transit (GIT), buyer's inventory, and supplier's finished production against the re-order point level (system inventory).

2.3. Green Supply Chain Management and Sustainability

Supply chain management (SCM) focuses on planning and strategizing to improve system cost, service level, and revenue management. However, a plethora of literature uses optimization approaches to support decision-making. A traditional optimization methodology as a goal-based approach fails to deal with the dynamic nature of environmental requirements (Sterman, 2010). The complex interaction of environmental, social, and economic challenges characterizes sustainability in a system (Seuring and Müller, 2008). Instead of a goal-based approach, sustainability is viewed as a never-ending process-based approach where the system needs to adapt and improve from feedback. As per Hjorth and Bagheri (2006), a process-based approach system requires a move from the traditional viewpoint to account for dynamic complexity from delays and non-linearity of environmental regulations. Prevailing literature on SCM sustainability fails to focus on the consequences of insufficient efforts toward sustainability (Hartmann and Moeller, 2014). As per Chopra et al. (2007), three groups drive SSCM: (i) reducing risk and improving supply chain performance, (ii) managing community pressures and governmental legislations, and (iii) attracting consumers who value sustainability.

Barriers associated with GSCM implementation include higher costs, coordination complexity/efforts, and insufficient/missing communication in the supply chain. As per Seuring and Müller (2008), focal firms manage external pressures and incentives from the government (regulator), customers (downstream), and stakeholders (internal and external). As a focal firm (with bargaining powers) in the supply chain, they face pressure from external and internal stakeholders to adopt/innovate toward more green practices (Hartmann and Moeller, 2014). Two stakeholder pressure groups, namely, customers and government, are particularly relevant (Seuring and Müller, 2008). Since the flow of pressure for green initiatives is considerably higher for large and high-profile firms/suppliers. In contrast, smaller suppliers away from end customers have few obvious incentives for improving their environmental performance (Lee et al., 2014). However, buying firms often pass this pressure onto upstream players, including smaller firms. Thus, the buyer-supplier relationship is crucial to transfer pressure and stimulate environmental change in SC (Matos and Hall, 2007).

Inherent complexities in global supply chains require collaboration and cooperation among members. But, with the recent trend towards sustainable goals, collaboration and cooperation among echelons have become necessary (Sarkis et al., 2011). A single value chain actor cannot invoke key sustainability initiatives under complex global production systems (Von Geibler, 2013). Co-operative approaches are likely more fruitful than large firms making suppliers mandates to comply with sustainability norms (Sharfman et al., 2009). Developed as a collaboration of non-state actors with a code of conduct, controlling sustainability in far-reaching chains gets difficult (Frostenson and Prenkert, 2015). Collaboration engagement depends on inter-firm trust, degree of uncertainty, and proactive environmental management (Sharfman et al., 2009). An open question still in literature is identifying a boundary regarding responsibility for the individual focal firm and how much resources should be devoted to it (Egels-Zandén, 2007).

2.4. Green Bullwhip Effect: Amplification of environmental requirements

Environmental regulation is a mandate the environmental regulator (government) imposes on a supply chain (Zhou et al., 2019). Environmental pressure is classified as pressure asserted by the downstream echelon for environmental practices (Lee et al., 2014). Figure 2 represents an interplay between *environmental regulations* and *environmental pressure*. Significant actors, government, and stakeholders assert internal and external pressure for green practices (Seuring and Müller, 2008). Sustainability requires defining individual *environmental restrictions* for operations under environmental regulations from regulators and environmental pressure from the downstream echelon. Environmental restrictions are management decisions for operations based on overall environmental requirements.

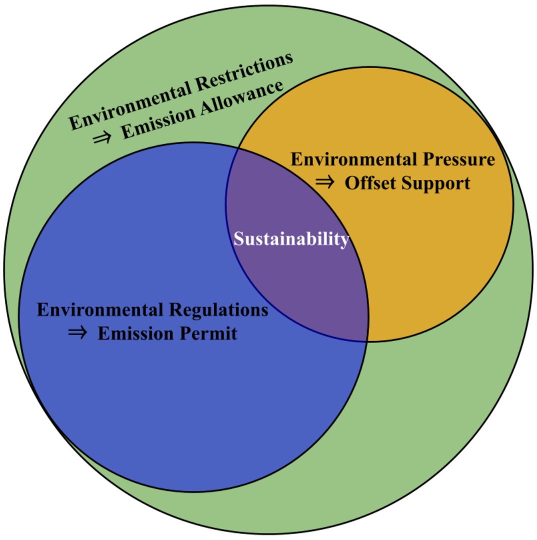

Figure 2: Interplay of Permit, Allowance, and Support as environmental requirements: Challenge to define restrictions to ensure sustainability

Propagation of environmental pressure into the supply chain introduces the green bullwhip effect (Lee et al., 2014) as environmental requirements are passed upstream. Further arguments for green bullwhip are supported by Laari et al. (2016) and Asgary and Li (2016) suggested as significant damage to firms' goodwill due to unethical operations. Distortion of information from end customers toward the upstream echelon with uncertainties reflects the impact on inventory and supply lines (Lee et al., 1997). As customers get rigorous and restrictive due to dynamic environmental issues, adjustments related to such responses introduce operational inefficiencies into the system, causing the (green) bullwhip effect (Laari et al., 2016). Due to uncertainty associated with environmental requirements at the immediate echelon, a buffer is incorporated to avoid risk aversion by individual echelons. Usually, this buffer is utilized to deal with upstream echelons' poor compliance with environmental deadlines (Lee et al., 2014) and downstream dynamic environmental pressure. As focal firms, upstream echelon contribute to leadership in innovation and supply chain collaboration (Seuring and Müller, 2008). Under green bullwhip, the focal firm needs more stringent environmental performance than that demanded by regulations using indirect regulations.

Likewise, classical bullwhip described by Lee et al. (1997) uncertainty towards a demand for upstream tier in the supply chain due to information distortion from the end customer. Dolgui et al. (2018) describes an impact of disruption propagation on supply chain performance due to changes in structural design and planning parameters as a ripple effect. An event-driven change in environmental requirements, such as a new regulation or practice incorporated, creates risks and uncertainties and complicates managerial response in the supply chain. Green Bullwhip Effect (GBE) is a dynamic response towards environmental issues in the supply chain, where environmental requirements of the downstream echelon become more rigorous and restrictive for the upstream echelon (Seles et al., 2016). Typical characteristics of such a system include rigor of demands on products and materials based on environmental characteristics (as move upstream), the deadline to meet environmental requirements tends to get shorter, and the response of green bullwhip depends on the buyer-seller relationship (Lee et al., 2014).

2.5. *Quantifying environmental requirements: Emission Permit, Emission Allowance, and Emission Offset*

All environmental requirements in the supply chain are quantified into emission permits, allowances, and pressures under the *Emission Permit System* (EPS) class. An EPS is an overall class of market-based systems that certify firms for compliance-based (or voluntary-based) on mandated regulators, specifically the government (Zhou et al., 2019). EPS keeps the firms under stakeholders' (governmental and public) scrutiny and requires dealing with institutional pressure from these stakeholders (SUN, 2014). Under EPS, an *emission allowance* (EA) encompasses both *emission permits* (EP) and *emission offsets* (EO). As Ellerman and Buchner (2007) described, EP mirrors traditional command-and-control measures by setting caps on individual or sectoral emissions, often declining over time to enforce strict environmental mandates by regulators. EO, in contrast, introduces a market for Verified Emission Reductions or Voluntary Emission Reductions, allowing firms to offset their footprint by purchasing credits from diverse sources like carbon sequestration projects (Griscom et al., 2017) or existing carbon markets (Convery, 2009). Flexibility between EP and EO incentivizes cost-effective reductions, allowing firms to choose between internal mitigation or leveraging cheaper offset markets (Chevallier, 2013). *Emission Allowance* (EA) ensures operations under compliance with the environmental restrictions for an individual echelon. As a regulator via EP (environmental regulation), it pushes for green practices, but a delay in transition requires reliance on the carbon market to ensure primary operations using emission offsets. EP and EO constitute EA to ensure supply chain operations are carbon-neutral (or net-zero).

2.6. *Net-zero Operations*

At an aggregate level for an individual echelon, two key decisions influence operations, "how much to produce?" and "how much to store?" (Disney and Towill, 2003a). An inefficient inventory management policy contributes to high costs and diminished service levels. Literature by Bijulal et al. (2011) studied the impact of operational policies on cost and service level. Introducing an additional constraint to make individual operations net zero toward green practices pushes the system to balance the trade-off between environmental and operational costs against service level (Deval and Venkateswaran, 2023b). To ensure operations are net-zero, strict compliance with EA is necessary for a period at the individual echelon. As per Bayon et al. (2012), companies and organizations are pushing to develop carbon-neutral products. Given a mandate by the regulator for environmental regulation, operational boundaries for an echelon are extended to decide on emission offsets for net-zero environmental compliance. Under strict environmental regulations, a regulator imposes a penalty for non-compliance, incurring additional costs (Benjaafar et al., 2012) to achieve the desired service level. To balance the trade-off between service level and system (operational and environmental) cost, emission offsets provide the opportunity to ensure a net-zero target with a balanced cost and service level for operational decisions.

3. From environmental requirements to Ripple Effect: Impact of environmental restriction on a cascade of PICS

As Seles et al. (2016) identified with low flexibility at the downstream stream echelon, pressure is asserted as part of the buyer-supplier relationship from the downstream to upstream for incorporating environmental practices.

Qualitative studies in the existing literature by Lee et al. (2014); Asgary and Li (2016); Seles et al. (2016) presented a narrative for pressure amplification as requirement moves upstream, assuming focal firms hold high leverage to introduce sustainable environmental practices. As an event-driven change in environmental requirements (Lee et al., 2014), a green bullwhip propagates environmental pressure towards green practices. Dolgui et al. (2018) defines ripple effect as an impact of disruption propagation on supply chain performance and disruption-based scope of changes in supply chain structural design and planning parameters. Intending to translate all environmental requirements based on emission offsets, emission permit, and emission allowance for quantification; a change in environmental (uncertain) parameters or structural change in operation propagates environmental requirements for the upstream echelon. Under individual environmental requirements, the ripple effect (from green bullwhip) for environmental pressure with classical bullwhip from uncertain demand introduces a new challenge towards ensuring sustainability. For the given supply chain below as a cascade of PICS under PER feedback, the sustainability problem is translated into ensuring smooth operations (balance the trade-off between cost and service level) under environmental compliance (pressure asserted by the downstream echelon and the regulator's environmental regulation).

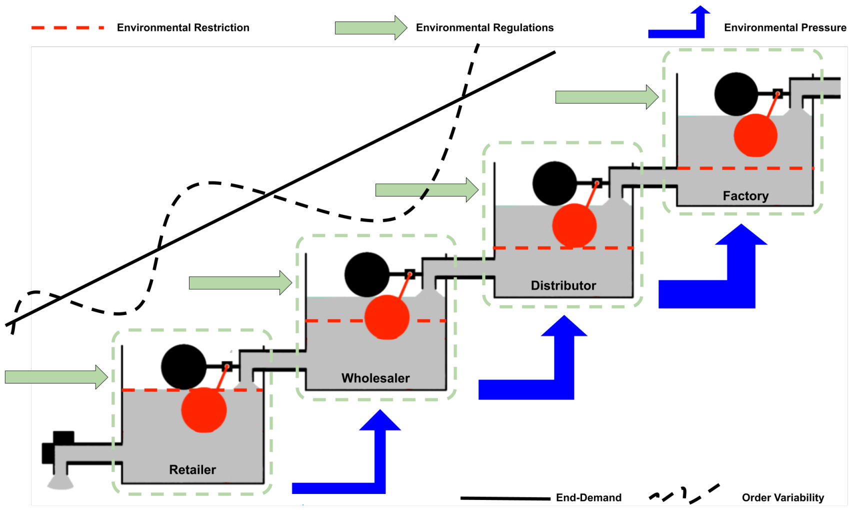

Figure 3: Green Bullwhip: Amplification of environmental requirements in multi-tier supply chain

A solid black line represents end-customer demand and a whipping order due to classical bullwhip increasing order variability as orders are passed to the upstream echelon. Assuming the individual tier in SC has a regulator dictating environmental regulations (refer to green solid arrow in figure 3). Considering environmental regulations mandated by regulators and environmental pressure by other stakeholders (downstream and upstream echelon) pushes for green practices. To ensure compliance, environmental restrictions (dashed green box in figure 3) are imposed independently by an individual echelon. Based on the restriction, operational policies are modified based on environmental feedback. The blue-bended arrow in figure 3 above depicts the ripple effect for propagation of environmental pressure as information is passed upstream echelon.

3.1. Quantifying green bullwhip: An amplification environmental requirement

With an emission permit (EP) imposed by the regulator, a tightening of environmental regulations at any echelon asserts pressure on the upstream echelon to provide emission offset support. Assuming the upstream echelon (say, supplier) with higher flexibility to incorporate green practices from existing buffer (Lee et al., 2014) of EP, pressure from the downstream echelon (say, buyer) pushes for the diffusion of green practices upstream (Green et al., 2000). Such diffusion of green practices widely involves collaboration to minimize the environmental impact (Seuring and Müller, 2008) of stringent environmental regulation in the buyer-supplier relationship. Pressure to share emission offsets by the supplier against the buyer's discrepancy in compliance redefines a collaborative approach in the buyer-supplier relationship. A contract between buyer-suppliers to minimize environmental costs is explored under this sustainable relationship. Supplier agrees to support emission offsets from an existing buffer of emission permits to improve end-customer service level (CSL) and maintain competitive advantage. The challenge is to balance operational cost (holding and backlog) and service level at the economic dimension, environmental cost, and downstream echelon pressure.

Simulation Setting

Assuming a random demand is observed by the buyer from end-customers, based demand, the buyer forecasts future demand along with adjustment to WIP and INV (refer to B1 and B2 loop in figure 1) to place orders with supplier for each period. Emission Adjusted Orders (EAO) further correct orders to ensure compliance with environmental restriction (refer to B3 loop in figure 1) of individual echelon using discrepancy between perceived emission rate (PER) and emission permit (EP). With two exogenous variables in the system, Customer Demand and Emission Permit push the system for operations under environmental requirements. Orders (or Production Release) of buyers is a customer demand for suppliers that drives operations under environmental requirements. The supplier follows a similar buyer structure independently to ensure smooth operations.

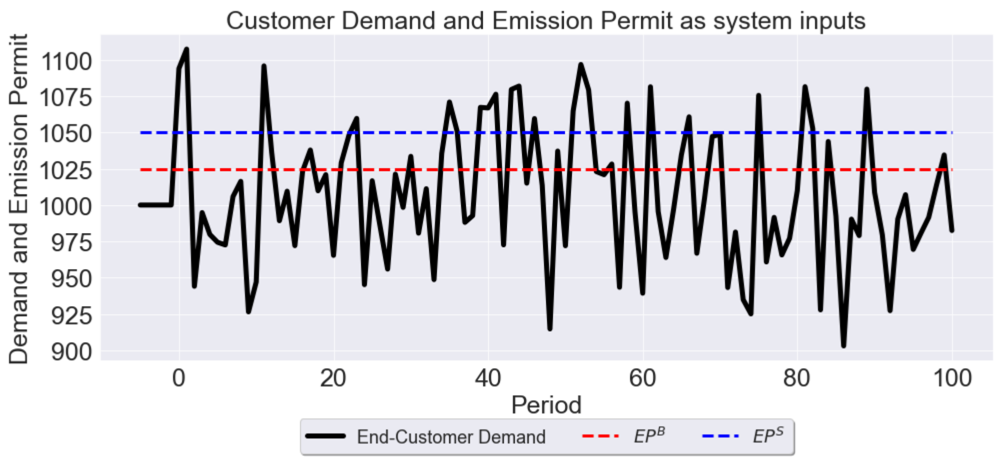

Figure 4: System Inputs: Customer Demand and Emission Permit for Buyer and Supplier

Demand is assumed to be constant with 1000− units until period 0 followed by a normal disturbance to a buyer from the end-customer with known mean, $\mu^B_{demand} = 0$ and standard deviation as $\sigma^B_{demand} = 50$. A constant lead time or supply delay for buyer and supplier of 3− period of time units is considered. For more details about the simulation, refer to Deval and Venkateswaran (2022a) for dynamics about PICS under PER feedback and Deval and Venkateswaran (2023a) for capacity up-gradation for PICS under PER feedback. Further, EP^B is the emission permit such that a maximum of 1025 unit $(1000+0.5\cdot\sigma^B_{demand})$ of production ensures net-zero operations for Buyer. Similarly, EP^S is emission permit such that 1050 $(1000 + \sigma^B_{demand})$ ensures net-zero compliance during production for supplier. Figure 4 below represents input into the buyer-supplier relationship.

Variability in demand from end customers will increase order variability as orders move from the downstream echelon to the upstream echelon as part of the bullwhip effect. Considering the introduction of environmental restrictions for individual echelons, ordering policies are modified per environmental requirements. A change in environmental regulation will introduce a ripple effect depending upon structural change or environmental parameters. Figure 5 represents variability in emission adjusted order (EAO) for the supplier depending on an assertion of pressure by the buyer.

Emission Adjusted Order (EAO) significantly reduces desired orders by ensuring Emission Permit (EP) compliance. Considering a given random demand and EP for buyer and supplier in figure 4 operations are performed in the buyer-supplier relationship for net-zero operations under the order-upto policy to ensure the stability of operations. Figure 5 represents a reduction in order (or PREL) for a period-based EAO to ensure compliance with environmental restrictions. The red line in the figure denotes EAO for the buyer, whereas the blue (solid and dashed) represents EAO for the supplier. Since the supplier is being placed at the upstream echelon, pressure is asserted by the buyer along with suppliers' existing pressure from the regulator. The dashed blue line represents the scenario when there is no pressure from the buyer; in contrast, the solid blue line represents a situation where the supplier also complies with pressure from the buyer. Considering the demand pattern with randomness will introduce order variability, that is, bullwhip, as a part of information distortion from the buyer. However, a ripple effect due to an event-driven stringent environmental regulation will also propagate pressure upstream, creating higher-order variability.

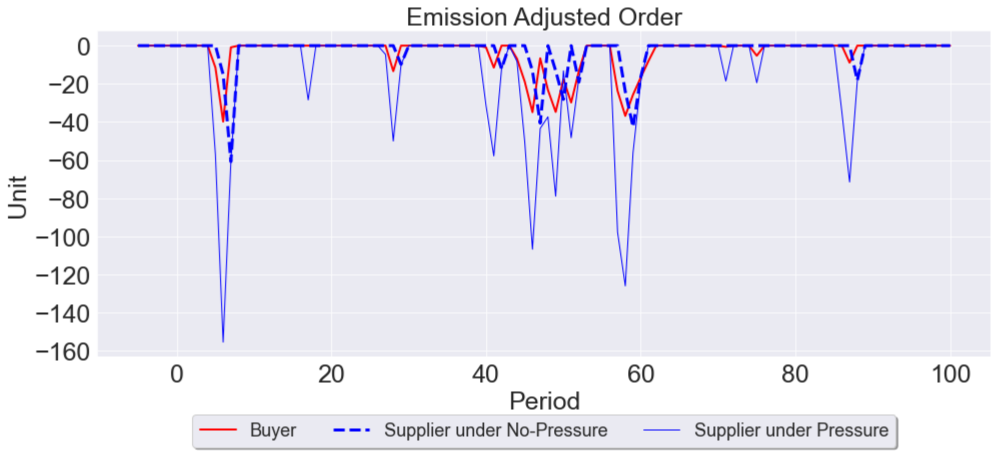

Figure 5: Emission Adjusted Order (EAO) for buyer and supplier under No-Pressure and Pressure

4. Ongoing Work

Managing a decentralized supply chain for efficiency and sustainability can be a complex challenge, especially with the "green bullwhip effect" amplifying environmental impacts. Sharing information and collaborating across the supply chain is crucial for its success. However, vendor-managed PICS (VM-PICS) under emission feedback can offer a promising solution. This enhanced VMI system integrates environmental considerations into traditional inventory management. It factors restrictions, regulations, and pressures from each echelon to balance environmental goals with overall supply chain costs. VM-PICS under emission feedback can reduce emissions as cost savings, improved environmental compliance, and a reduced environmental footprint. By embracing VM-PICS under emission feedback and continuously adapting to evolving requirements, firms can navigate the complexities of decentralized supply chains and create more sustainable operations.

Figure 6 proposes a Vendor-Managed Production and Inventory Control System (VM-PICS) framework under Emission Feedback. Consider the relationship between buyer and supplier such that the supplier is responsible for buyers' inventory management. A collaborative relationship removes a layer of unnecessary forecasting, leading to clearer and more visible demand at the supplier. Environmental requirements are derived from regulations that push each echelon to determine its environmental restrictions under the traditional setup. As the literature supports based on various case studies, environmental pressure is passed from downstream to upstream, assuming the upstream echelon has more flexibility compared to downstream (Lee et al., 2014; Seles et al., 2016; Hartmann and Moeller, 2014).

Better forecast and reduced managerial hierarchy in decision support are critical characteristics of classical vendor-managed inventory. Additional visibility of buyers' environmental requirements and the demand to the supplier helps to modify suppliers' operational policies based on environmental regulation and reduces environmental pressure.

The work presented above is a part of ongoing research modeling and analysis of sustainable supply chain management. Based on the above preliminary work to quantify green bullwhip, a traditional buyer-supplier relationship requires further exploration for collaboration in an attempt to reduce system costs. A more detailed simulation-based analysis can be expected on these grounds regarding the buyer-supplier relationship. Further, sufficient literature supports the argument for the existence of green bullwhip as environmental requirements are amplified as it is passed upstream. The lack of quantitative literature fails to provide a mitigating strategy. Using PICS with PER feedback,

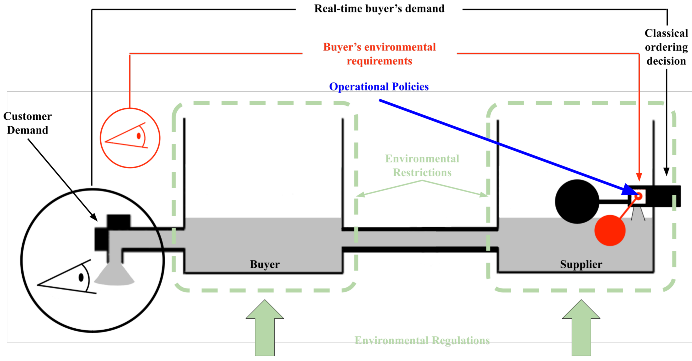

Figure 6: Vendor Managed Production and Inventory Control System (VM-PICS) under Emission Feedback

an initial attempt will performed to quantify green bullwhip with a mitigation strategy using Vendor-Managed PICS (VM-PICS) as a collaborative approach among echelons.

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