Dynamics of Emission-based Production and Inventory Control System and Carbon Market: Moving towards an integrated framework

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Abstract

This paper proposes using technological transition and a carbon market in the EPICS model. Sub-unit of capacity upgradation is used to reduce unit emission as a long-term system objective via., a clean technology transition modeled using the Bass Diffusion model for technological forecasting. The delay involved in the transition requires the system to have a short-term solution for carbon credit from a fictitious carbon market (another sub-unit). A modified stock management structure determines ordering/buying decisions for a deficit/surplus in carbon credit to increase/decrease Emission Allowance for smooth operations without higher environmental costs. This paper is the first step toward creating a generic model to understand the interplay in operations for the above three sub-units for long-term and short-term decisions. Sub-units are simulated under various scenarios for POUT policies to determine dynamics and costs associated with selected parameters. Average Cost (holding and backlog) and Environment Cost (Emission Cost, Revenue, and penalty) are considered performance measures for the POUT policy in the system. Initial results suggest that the choice of control parameters significantly impacts the system and environmental cost.

Keywords*: APIOBPCS, EPICS, Carbon Market, System Cost, Environment Cost, Emission Allowances, Perceived Emission Rate, Emission Permit*

1. Introduction

Emission-based Production and Inventory Control System (EPICS) as a powerful tool reduces carbon footprint while ensuring operational efficiency at a minimal cost. Under EPICS environmental regulations are mandated by the regulator (usually the government) to abide into system operations. These regulations have created carbon markets globally for the exchange of carbon credit given greenhouse gas (GHG) reduction as an objective using incentives and penalties mechanisms. This study attempts to integrate EPICS with a carbon market to ensure smooth system operations.

1.1. Literature Review

Production and Inventory Control Systems (PICS), in general, will affect the environmental (emission) footprint. Optimization models consider the carbon emission level a soft constraint and use optimization heuristics for optimal ordering quantities depending upon the system setup level of player collaboration [Benjaafar et al. (2012)]. The focus on emission reduction should be at the grassroots level of manufacturing, transportation, and, more importantly, operational aspects. Recent literature suggests using Economic Order Quantity (EOQ) techniques to order optimal quantities with emission considerations. Hua et al. (2011) proposed an EOQ model with a carbon-cap trade mechanism for emission reduction and total cost trade-off against no emission considerations. Chen et al. (2013) derived analytical support for a significant reduction in emissions without significant cost increment. But such an approach needs to account for nonlinear thinking based on individual rationality [Sterman (2000)]. For achieving the green target in a supply chain system feedback-based on environmental impact in decision-making and cost minimization [Deval and Venkateswaran (2022a)]. A feedback-based approach instead of linear thinking helps a system grow sustainably.

Considering Sustainability is an unending process defined neither by fixed goals nor the specific means of achieving them, but by an approach to creating change [Hjorth and Bagheri (2005)]. Thus, it is necessary to use a system dynamics approach to study sustainability in supply chain management problems. Over the years, the Inventory and Order-based Production Control System (IOBPCS) family has significantly improved in its variants using the feedback-based approach by creating an automated pipeline inventory and order-based production control system (APIOBPCS) [Simon et al. (1994)].

It considers discrepancies between desired-level and actual level of work-in-process or supply line providing stability to the system. A substantial literature on the IOBPCS family of systems varying from the study of system stability and controllability [Disney et al. (2004, 2005), Dejonkheere et al. (2003), Oregta and Lin (2004), Venkateswaran and Son (2007), Disney and Towill (2002)]. With two possible extrema of policies, No-feedback, and CNE-feedback, PER-feedback between them suggests losing partial demand in the short term and reducing CNE marginally over time [Deval and Venkateswaran (2022a)]. Deval and Venkateswaran (2022b) introduced EPICS in a continuous time domain and studied stability analysis for PER feedback. Further, introducing emission feedback to the system causes compromise with partial demand. Thus, a reduction in system emissions is required as part of capacity upgradation [Deval and Venkateswaran (2022b)].

As per Akkermans et al. (2003), capacity design is a one-time decision. But due to long-term technological developments and decreasing product life cycles, a balanced approach toward the investment rate is needed. System resources are limited and financially expensive, involving a delay in utilization. Thus, deciding optimal efforts to maximize service level and minimise system cost is a complex challenge. A comprehensive analysis by Ceryan and Koren (2009) suggests critical financial decisions in a company are typically made only when strategic decisions about investment or disinvestment are clear-cut and are categorised as periodic decisions. Short-term operational adjustments are needed to achieve the desired sustainability target [Deval and Venkateswaran (2022b)]. As a part of the long-term objective for the system's sustainability, capacity upgradation (note not capacity expansion) is required in the form of bringing cutting-edge technology for operational purposes to bring down unit emissions via., clean technological transition and investing in long-term capacity upgradation.

The above feedback-based approach is the missed-out model of clean transition for capacity upgradation. To model the transition in the above EPICS, an assumption about the system's operational activities will continue to improve as clean technology is available and adopted by the firm. Ideally, such a crude assumption is unrealistic due to the uncertainty involved in innovation, but classical literature supports technological forecasting [Kucharavy and Guio (2011)]. A trend for innovation in literature is well known S-shaped phenomenon and is widely accepted by the community of society, environment, scientists, entrepreneurs, and many more. Some applications of S-shaped growth include technological forecasting [Ayres (1969)], innovation theory [Rodgers (2003)], and substitution of new products/processes from old ones [Fisher and Pry (1971)].

Furthermore, the International Institute of Applied System Analysis (IIASA) identified possible domains to use S-shaped in the future of primary energy sources and vectors; evolution of agricultural technologies; development of discoveries; environmental changes and problems, and many more [Kucharavy and Guio (2011)]. Typically, the innovation of many products follows an S-shaped curve [Kijek (2015)] whereby in the beginning phase, the acceleration in the performance of a product is slow. In the middle phase, a product's performance is rapidly accelerating. Finally, the performance of a product achieves saturation, and there is limited improvement in its performance. S-shaped and envelop curves have been applied for technological forecasting since the 1960s [Ayres (1969)]. Logistics and enveloping curves show fascinating results for lighting systems, particle accelerators, aircraft, microelectronics, transportation systems, and energy conversion technologies [Kucharavy and Guio (2011)]. The diffusion innovation by Everett M. Rodgers (1962) postulated that innovations would be spread in society in an S-curve. Since innovation involves both the learning process and the introduction of new technology, therefore using Bass Diffusion Model [Kucharavy and Guio (2011)] for the diffusion of innovation below module is proposed for technological innovation.

Dinda (2018) and Reis (2001) modeled the rate of pollution directly proportional to the output and indirectly proportional to the clean technologies available. Bass Diffusion (1969) adoption of new products from non-users to users based on system feedback of advertising effect and word-of-mouth. So, the transition to clean technology from non-clean technology will be based on Knowledge and Obsolescence.

With innovation and the development of relevant ecological and environmental systems, emission control can be achieved. An Emission Permit System (EPS) is widely used worldwide as a certification program and determines specific requirements that firms must comply with as a commitment to government regulations. Such a system has effectively managed fixed emission sources and contributed towards improved environmental quality [Zhou et al. (2019)]. EPS keeps the firm under stakeholders' (governmental and public) scrutiny and requires dealing with institutional pressure from stakeholders [Sun (2014)]. Sarkis et al. (2011) used stakeholders and institutional theory to analyze Green Supply Chain Management (GSCM) and suggested that stakeholders exert significant environmental/institutional pressures and influence and adopt GSCM practices. But still, an unclear picture of institutional forces related to adopting various environmental management practices in GSCM pertains [Zhu et al. (2016)]. The exciting challenge is understanding the impact of institutional pressure on the diffusion of adoption of GSCM practices in supply chain management [Seles et al. (2016)].

This study proposes an integrated framework model using EPICS and capacity upgradation with a carbon market to understand the dynamics for the overall feedback of such a system. Section 2 describes the sub-units required in the framework model, Emission-based Production and Inventory Control System (EPICS), Clean Transition, Carbon Market, and cost performance measures used in the study. In section 3, the simulation is performed for an integrated model under various scenarios and parameter settings. Finally, some key observations and conclusions are drawn from this study in section 4.

2. System Model

2.1. Emission-based Production and Inventory Control System

A Production and Inventory Control System (PICS) is an effective mechanism for dealing with Production-Inventory (PI) decisions in a production process. Existing literature uses A(V)PIOBPCS (refer to literature review section), where the feedback-based approach with control parameters ensures system dynamics are maintained as per desired level. A Stock-Flow representation of APIOBPCS as a generic stock management problem is presented by Sterman (2000). Stock Management Structure (SMS) can be modeled to represent Inventory Management, Capital Investment, Real Estate, Agricultural Commodities, and many more. Control parameters selection plays a crucial role in such a system and can bring oscillations and instabilities. Classical stock management structure accounts for the current state of the system in comparison desired state for decision-making. Instabilities and oscillations from the bounded rationality of the decisionmaker cause the system to incur a higher system cost or other consequences like boom-and-bust cycles. This feedback-based approach needs to consider environmental impact due to poor decision-maker judgment.

As per Deval and Venkateswaran (2022a, SD), Cumulative Net Emission (CNE) feedback ensures the system reaches to net-zero target, whereas Perceived Emission Rate (PER) accounts for only some operational adjustment to ordering decision-based on change of perception of actual emission rate. A PER-feedback sandwiched between CNE-feedback and No-feedback ensures that both system emission and cost can be minimized with policy intervention from a combination of both CNE-feedback and PER-feedback. An Emission-based Production and Inventory Control System (EPICS) proposed by Deval and Venkateswaran (2022b, IEEM) accounts for PER-feedback for ordering decisions. As suggested in the study, the choice of adjustment rate reduces the system's emission footprint but with a compromise in service level. This article develops insights into the dynamics of the capacity upgradation of EPICS using long-term capacity upgradation via., technological interventions.

A single manufacturer (with an *order-to-make* approach) based on emission level manages to order by adjusting Production Release ($PREL$) via. Emission Adjusted Orders (EAO). Figure 1 below provides a stock management structure for EPICS. The black causal links represent classical APIOBPCS, and the blue causal links represent PER-feedback to the system. Literature by Deval and Venkateswaran (2022a, 2022b) explores the dynamics of PER-feedback and the continuous-domain stability analysis of EPICS. Below are set of the difference equation for EPICS from equation (1)-(10) [Deval and Venkateswaran(2022b)].

$$PREL_n = FD_n + adjWIP_n + adjINV_n + EAO_n \tag{1}$$

$$FD_n = FD_{n-1} + \rho(FD_{n-1} - CD_{n-1}) \tag{2}$$

$$adiWIP_n = \alpha(DWIP_n - WIP_n) \tag{3}$$

$$adjINV_n = \beta(DINV_n - INV_n) \tag{4}$$

$$WIP_n = WIP_{n-1} + PREL_{n-1} - PCR_{n-1} \tag{5}$$

$$INV_n = INV_{n-1} + PCR_{n-1} - CD_{n-1} \tag{6}$$

$$PCR_n = PREL_{n-L} \tag{7}$$

$$EAO_n = \gamma \frac{EP_n - PER_n}{e} \tag{8}$$

$$PER_n = PER_{n-1} + \tau(PER_{n-1} - AE_{n-1}) \tag{9}$$

$$AE_n = e \cdot PCR_n \tag{10}$$

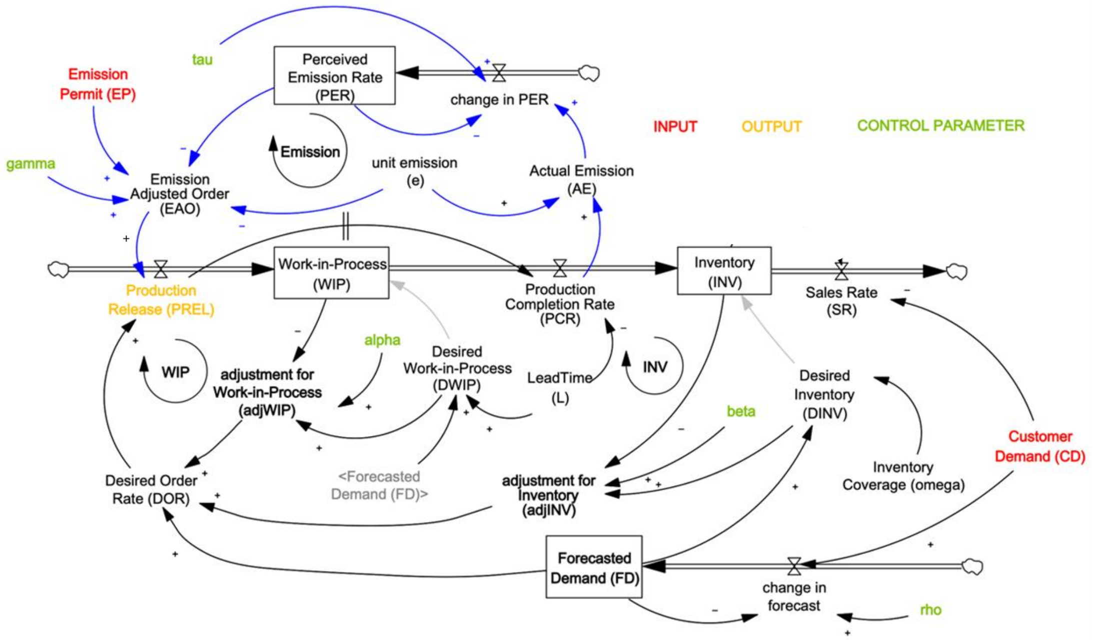

Figure 1: Stock Management Structure for Emission-based Production and Inventory Control System (EPICS)

Consider eq (1) together with (3) and (4), under Pure Order Up-To ($POUT$) i.e., $\alpha = \beta = 1$ for $\omega = 1$ below as eq (11). $(L+2) \cdot FD_n$ is known as Order-Upto (OUT) level, and the expression $WIP_n + INV_n$ is Inventory Position in the system. Also in contrast, EAO_n is an additional adjustment to ordering based on system emission.

$$\begin{aligned} PREL_n &= FD_n + DWIP_n - WIP_n + DINV_n - INV_n + EAO_n \\ &= FD_n + L \cdot FD_n - WIP_n + \omega \cdot FD_n - INV_n + EAO_n \\ &= (L + \omega + 1) \cdot FD_n - (WIP_n + INV_n) + EAO_n \end{aligned} \tag{11}$$

In classical APIOBPCS two balancing loops namely, the adjustment to Work-in-Process loop and adjustment to the Inventory loop control system with adjustment rate α and β respectively. In Figure 1, feedback loops correct discrepancies between WIP and INV against the desired level. Note that $\gamma = 0$ implies the above EPICS as classical APIOBPCS. Further, a periodic review system of form (R, s, S) with unit demand is equivalent to the continuous review system (s, S) (Axsäter, 2000). Herein, S is the order-up-to (OUT) level, and R is the review period; thus, inventory position (IP) is $s = S - 1$ at review period R for unit demand. Therefore, the policy gets modified as $(R, S - 1, S)$ triggering $S - s$ as order quantity to ensure inventory is S. But with additional balancing feedback from PER, EAO operational adjustment about emission to $PREL$ is required depending upon the state of the system for emission. This feedback causes the system to order more or less than OUT level depending upon the discrepancy between Emission Permit (EP) and Perceived Emission Rate (PER). Such an argument holds true for the system with General Order Up To ($GOUT$) level i.e., $\alpha \neq 1$ and $\beta \neq 1$. Additional feedback in the system is required as part of policy intervention to ensure a better service level for the system is achieved at minimal system cost.

2.2. Capacity Upgradation: Long-term Technological Intervention

As discussed above, feedback from the emission refrain system is to reach desired steady state (OUT level, S or higher service level). Thus, additional feedback is required in the system to reduce unit emissions [Deval and Venkateswaran (2022a)]. This additional feedback to EPICS is part of “Capacity Upgradation” (different from efforts made towards capacity expansion or building). Herein capacity upgradation to the system is referred to technological interventions for unit emission (e) reduction by transitioning to clean technologies and building a decarbonization process for the system to increase emission allowance (refer to the literature review section to distinguish between Emission Permit (EP) and Emission Allowance (EA)).

EPICS as operational adjustment and capacity upgradation as part of strategic decisions, the overall system requires integration of two or more firms’ subunits for systems sustainability (define system sustainability). Decisionmakers operating in their respective domain are unaware of the overall feedback structure in the system. Thus, with limited information, the overall problem of system sustainability is reduced as the task of deciding for smaller sub-units. By establishing subgoals the complexity of the real problem is vastly reduced [Sterman (2000)]. But, these subunits of a real system bring individual dynamic complexities from delays, feedback, and non-linearities causing policy resistance, instability, and dysfunction. Likewise capacity expansion, this capacity upgradation to the system also requires a cautious approach due to risk factors and time delay [White and Censlive (2016)]. Thus, incremental changes such as improving the above production efficiencies to existing social-technical systems are no longer sufficient. There is a need to change the entire production and consumption systems to deal with sustainability challenges.

With an objective of a socio-technical transition toward net zero, a roadmap toward how such a system comes about and interventions in the context of transitions can be organized. As a part of the long-term intervention (short-term adjustment already accounted for from PER feedback), the existing system can be upgraded via., a long-term capacity upgradation loop for decarbonization and clean technology transition to reduce unit emission. Note that this study is restricted to understanding the impact of clean technological transition. But these efforts to reduce unit emissions are uncertain and involve delay; thus, investing in an alternative mechanism to reach the net-zero target becomes necessary.

1. Module for Technological Transition

Assume the system under consideration has no clean technology for production purposes and overtime management decides to move towards clean production. This transition of technological adoption can be represented by the Bass Diffusion model [Bass (1969)]. Two components drive the “Transition Rate” from “Fractional Non-Clean Technology” to “Fractional Clean Technology”: “Transition via., Knowledge” and “Transition via., Obsolescence”. Knowledge creation is an important aspect of innovation and the adoption of new technology. Kline and Rosenberg (2010) suggest that stored knowledge and how knowledge is corrected and added affect innovation. Also, this transition is driven by the obsolescence of existing technology. In this study, if some fractional clean technology is adopted, it will reinforce more non-clean technology to transition into clean technology.

This idealistic situation can be represented as a modified Bass Diffusion model in Figure 2.

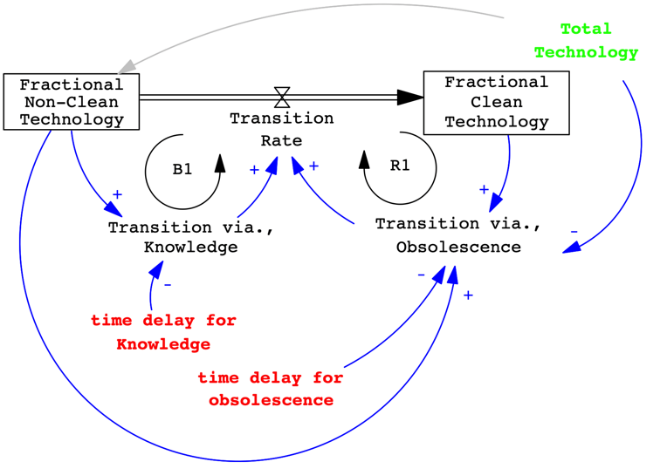

Figure 2: Stock flow structure for technological transition

The above system has two loops: $B1$ and $R1$ as balancing and reinforcing loops; thus S-shaped growth is expected as dynamics of "Fractional Clean Technology". But the rate of saturation depends on two-time delays defined in the above stock-flow diagram. "time delay for Knowledge" causes the transition to be proportional to "Non-Clean Technology" (first-order goal-seeking behavior). Whereas "time delay for obsolescence" causes the transition dynamics to be inverted bell shaped, and the higher the later delay results the more time for transition to "Clean Technology".

Emission as a by-product in EPICS is unavoidable and inherent with the Production Completion Rate (PCR). Technological improvement as a part of intervention can minimize the environmental impact of the production process. Unit emission (e) as a decreasing function of technological improvement such that Actual Emission (AE) generated from the system is directly proportional to PCR, and inversely proportional to "fractional clean technology" [Reis (2001), Dinda (2009)] i.e.,

$$AE_n \quad = \quad e \cdot (1 - CT_n) \cdot PCR_n \tag{12}$$

where, CT_n is the fraction of clean technology available at period n. Therefore, $(1 - CT_n)$ is a fraction of the non-clean technology used in the production process, $CT_n \in$

[0,1]. In extreme cases, $CT_n = 0$ implies no transition to clean technology and $CT_n = 1$ implies a transition to all clean technology with no emission from the production process.

2.3. Carbon Market: Short-term Cost

The carbon market facilitates buying and selling carbon credits or allowances to emit greenhouse gases (GHG), specifically carbon. Based on the " cap-and-trade" principle, a limit/cap is set by the market regulator, and deficit/surplus is bought/sold credit from/to the carbon market. To incentivize the system financially for reducing its carbon footprint, a dynamic carbon price on carbon emission driven by demand and supply of credit drives this carbon market. This market-based mechanism ensures system continues its operations by accounting carbon footprint. In this study, the carbon market, and Emission Trading System (ETS) are used interchangeably as both exactly serve the purpose of GHG reduction. But the two are slightly different due to the government's involvement. Under ETS, the government sets a cap on emissions as a centralized regulator whereas, the carbon market is decentralized and completely market-driven without a cap.

The global carbon market can be separated into two sub-markets: the compliance (or regulatory) and the voluntary market. As the name suggests this compliance (or regulatory) based market is underpinned in one way or another by the Kyoto Protocol. Three flexibility mechanism-based international compliance for regulation are available: (a) Emission trading (transaction between countries with target); (b) Joint Implementation (transaction between developed and economies in transition) and (c) Clean Development Mechanism (transaction between industrialized and developing countries) [Bayon et al (2012)]. On the contrary, voluntary carbon markets do not rely on legally mandated reductions to generate demand introducing criticism for lack of uniformity, transparency, and registration.

For an accounting of carbon, there are two approaches (a) territory-based approach and (b) footprint-based approach where the initial one is “production-based” and the latter one is a “consumption-based” approach [Brohé (2017)]. In this study, a production-based carbon accounting approach adopted as the system under consideration deals with emission at a single source, i.e., Production Completion Rate (PCR). Further, assuming Emission Permit (EP) is a constraint on production mandated by the regulator of a fictitious carbon market that is exogenous to the system. Any credit deficit can be bought from the carbon market at market price but must pre-place orders for next time period (this assumption aggregates the auction, exchange, and over-the-counter markets together). These additional bought credits contribute to Emission Allowance (EA) which is the sum of available Emission Permit (EP) and Credit Delivery Rate (CDR).

1. Module for Carbon Credit

A generic stock management structure like APIOBPCS (but with slight modifications) can be used to depict better decisions to maintain inventory of Emission Allowance (EA). Emission Allowance (EA) is defined as the accumulation of both an Emission Permit (EP) and additional credit from the carbon market, Credit Delivery Rate (CDR). Like APIOBPCS, push approach from Customer Demand (CD) drives the production process. Actual Emission (AE) drives buying/selling of additional credits. Credit Orders Rate (COR) is defined as pre-orders placed for the next time period in the carbon market for carbon credits. Thus, a lead time from placing an order, COR to delivery, CDR creates credits in transit represented as CIT. This credit (material) flow is well managed using anchor and adjustment heuristic and information flow.

EA is the net accumulation between EP, CDR, and AE whereas, CIT is the net flow between COR and CDR with fixed lead time $L_c = 1$. The desired level of these stocks (DEA and $DCIT$) is maintained as per Little's law [Venkateswaran and Hasti (2006)] using the Perceived Emission Rate (PER). Any discrepancy between desired and current levels is adjusted by placing additional credit orders to COR with α' and β' adjustment rates. Figure 3 below presents an SFD representation of the carbon credit module, which can be integrated into $EPICS$ via., Actual Emission (AE).

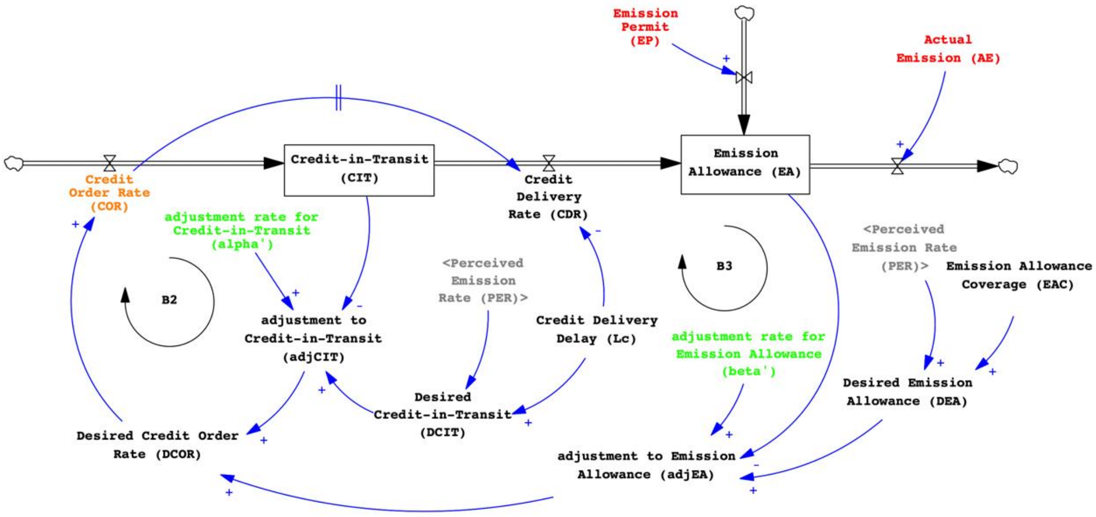

Figure 3: Stock flow structure of carbon credit module

2.4. System Performance: Average System Cost and Environment Cost

Average Holding Cost (AHC) and Average Backlog Cost (ABC) are considered as a system performance measure from classical setup [Bijulal et al.(2011)]). From an environmental perspective, three costs are associated with evaluating credit module performance, Average Emission Cost (AEC), Average Credit Revenue (ACR), and Average Environmental Penalty (AEP). Below is the set of equations used to model these performance measures.

Equations (13) and (14) below represent average holding and average backlog cost with c_h and c_b as cost coefficients respectively. Further, eq (15) represents the System Cost (SC) as the sum of holding and backlog costs. To model Environment Cost (EC), eq (19) can be referred to as components of emission cost, emission revenue, and emission penalty. c_e is the cost coefficient corresponding to eq (16) representing average emission cost i.e., buying additional credits from the carbon market. Equation (17) below represents revenue from selling surplus carbon credit into the market at price c_e. Since the regulator regulates the market, a high penalty (refer to eq (18)) is imposed for exceeding Emission Allowance (EA) with cost coefficient c_p.

$$AHC_n = \frac{1}{n}\sum_{i=1}^{n} c_h \cdot INV_i^+ \tag{13}$$

$$ABC_n = \frac{1}{n}\sum_{i=1}^{n} c_b \cdot INV_i^- \tag{14}$$

$$SC_n = AHC_n + ABC_n \tag{15}$$

$$AEC_n = \frac{1}{n}\sum_{i=1}^{n} c_e \cdot COR_i^+ \tag{16}$$

$$ACR_n = \frac{1}{n}\sum_{i=1}^{n} c_e \cdot COR_i^- \tag{17}$$

$$AEP_n = \frac{1}{n}\sum_{i=1}^{n} C_p \cdot 1_{EA<0} \tag{18}$$

$$EC_n = AEC_n + ACR_n + AEP_n \tag{19}$$

3. Simulations and Results

For simulation purposes, a system is assumed to initialize at dynamic equilibrium by setting control parameters. The dynamics focus on $POUT$ policy, i.e., $(\alpha, \beta) = (1, 1)$ with lead time as 3-time units. Smoothing parameters for CD and PER i.e., ρ and τ are 0.25 with a random normal demand having a mean 100 and a standard deviation of 10 such that coefficient of variation is 0.1. The results presented below are extensions of Deval and Venkateswarn (2022,a) with technological intervention and carbon-market module to understand dynamics and system performance in terms of cost. Figure 2 above depicts a stock-flow management structure for a clean technology transition with expected dynamics to be S-shaped growth in clean technology adoption. So, for reference, the transition dynamics as per Figure 4(a) are considered to reduce unit emission via., eq (12). CD and EP are exogenous variables to the system with inventory coverage (ω) and Emission Allowance Coverage (EAC) as 1-time units.

The system setting for the carbon market is set at a state of dynamic equilibrium using Little's law. A lead time of 4-time units as Credit Delivery Delay (Lc) ensures credit bought are not immediately available for use. The discrepancy between the desired and actual level of credit in this credit module is adjusted using $POUT$ policy i.e., $(\alpha', \beta') =$

$(1, 1)$. A cost vector under consideration for various cost coefficients is given as $[c_h \quad c_b \quad c_e \; -c_e \quad c_p] = [1 \quad 2 \quad 1 \; -1 \quad 100]$. RK-4 method of integration for smallest time step is used to simulate the above-integrated setup in Vensim® with normal CD and EP as per Figure 4(b).

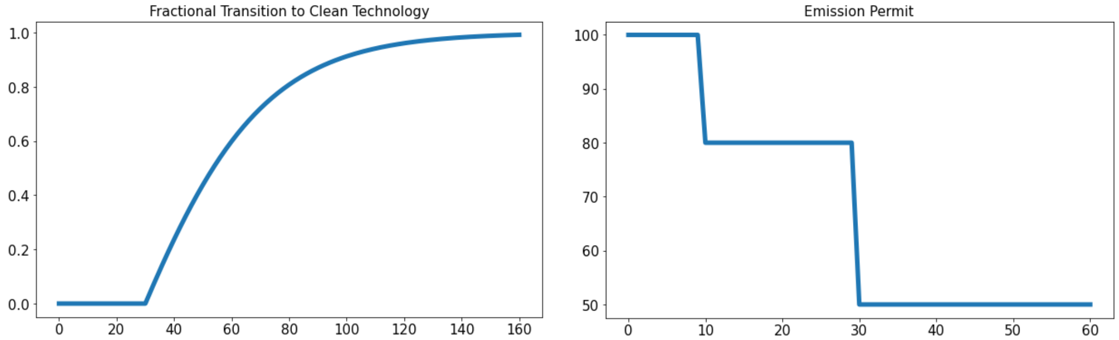

Figure 4: (a) Dynamics of clean technology adoption/transition and (b) Emission Permit

1.1. Initial Scenarios

The following are four scenarios considered in the initial simulation setup.

(a) Base Case: $POUT$ policy with $\gamma = 0$

(b) Scenario A: POUT policy with $\gamma = 1$

(c) Scenario B: $(\alpha, \beta, \alpha', \beta')$ = $(0.5, 1, 0.5, 1)$ with $\gamma = 1$

(d) Scenario C: $(\alpha, \beta, \alpha', \beta')$ = $(1, 0.5, 1, 0.5)$ with $\gamma = 1$

In Figure 5(a) below dynamics of Inventory (INV) level and Production Release $(PREL)$ rate are presented for the above-considered scenarios. As expected for Base Case, $\gamma = 0$ implies no emission feedback on ordering i.e., classical APIOBPCS setup. Both INV and $PREL$ (refer to the blue curve in Figure 5(a) and (b)) depict a damped oscillation due to the standard deviation in CD. Under this setup, the system is completely independent of other dynamic complexities. On the contrary, when feedback is accounted to ordering i.e., Scenario A, B, and C at $\gamma = 1$ i.e., full weightage to adjustment to $PREL$ via., EAO some exciting dynamics are observed. A steep reduction in $PREL$ can be observed in Figure 5(b) for orange, green, and red curves due to the regulator's sudden reduction in EP. This sudden event causes inventory to deplete as insufficient orders are placed in $PREL$ and a buffer from inventory coverage is used to serve customer demand. Consider Figure 5(a) where inventory dynamics are presented, a higher weightage to inventory adjustment rate ensures the system responds by ordering higher if inventory is below the desired level. Scenario B and C (refer to orange and green curves) places order to replenish to ensure the desired level is immediately reached. Unfortunately, EAO refrains the system to reduce desired order and WIP introduces a delay in reaching the desired level. However, lower weightage to β in Scenario C (red curve) cause the system to reach the desired inventory level slower. Interesting to note here is the variability in scenarios A, B, and C of $PREL$ (refer to Figure 5(b)), higher weightage to α and α' than β and β' cause the system to more adjustment to PREL than giving higher weight to inventory adjustment parameters β and β'.

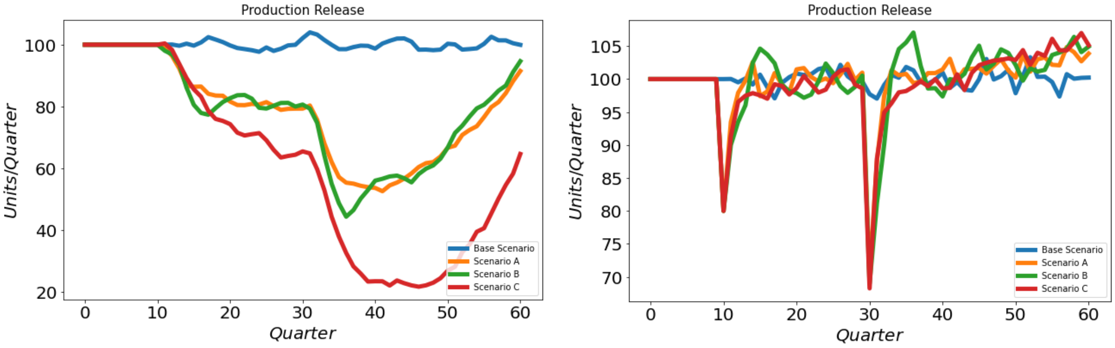

Figure 5: Dynamics of (a) Inventory and (b) Production Release

1.2. Sensitivity of γ on System Emission

In Figure 6 below dynamics of various system emissions are represented. Actual Emission (AE) represented as a blue curve is the emission rate from the production process which is directly proportional to unit emission (e) and inversely to the fraction of Non-clean technology (CT_n) in the system. The orange curve denotes the Emission Permit (EP) imposed by the regulator for operational purposes and is a completely exogenous system. Insufficient allowance cause system to buy additional allowance from carbon market at the carbon price. Emission Allowance (EA) given in green in the below figure is the sum of both EP and Credit Delivery Rate (CDR). Red curve in the below figure is Credit Order Rate (COR). Though dynamics on $POUT$ policy are almost exact but Table 1 below represents the choice of control parameter can significantly reduce system cost.

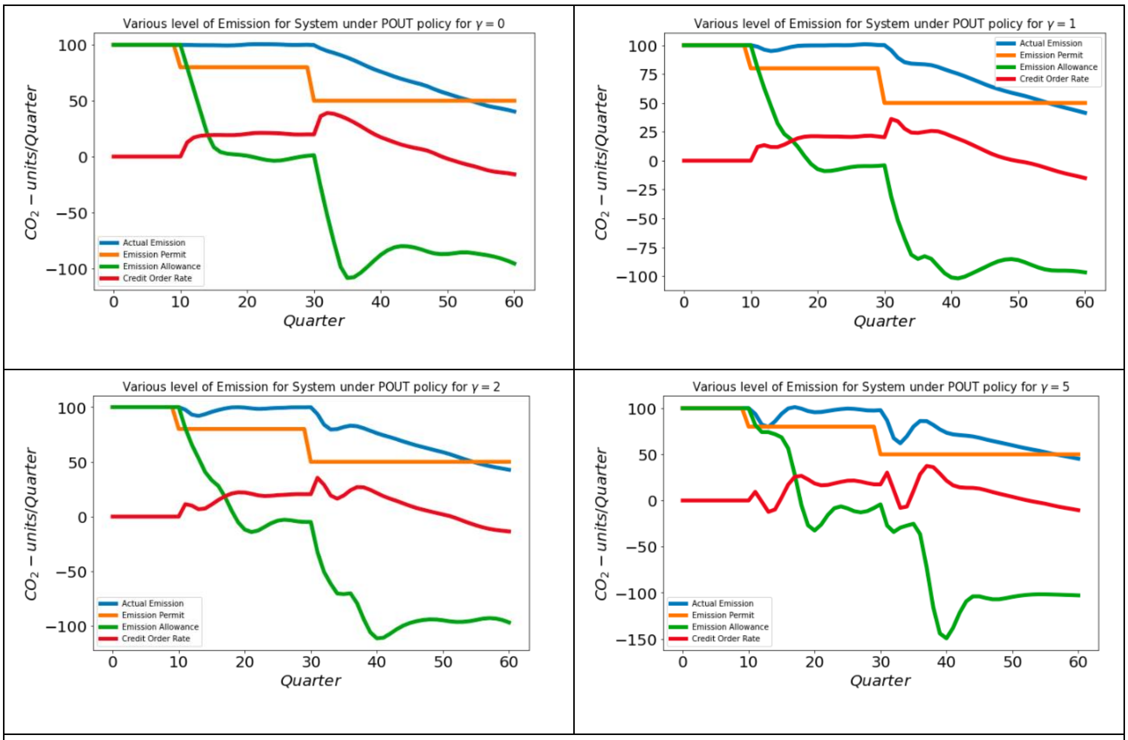

Figure 6: Dynamics of Actual Emission (AE), Emission Permit (EP) and Emission Allowance (EA) along with Credit Order Rate (COR).

In Figure 6 above dynamics are presented under $POUT$ which initial observations suggest insignificant but, an observation from Table 1 as the weightage γ is increased Average Cost (AC) is significantly reduced compared to lower γ weightage. Furthermore, lower weightage to α, β, α' and β' has some role in reduced AC and thus requires investigation for choice of the control parameter.

Table 1: Sensitivity of γ on Average Cost (System and Environment Cost)

$(\boldsymbol{\alpha}, \boldsymbol{\beta})$	$(\boldsymbol{\alpha}', \boldsymbol{\beta}')$	$\boldsymbol{\gamma}$	$\boldsymbol{SC}$	$\boldsymbol{EC}$	$\boldsymbol{AC}$
$(1,1)$	$(1,1)$	0	101.50	69.14	170.64
$(1,1)$	$(1,1)$	1	79.66	80.73	160.39
$(1,1)$	$(1,1)$	2	58.35	80.34	138.69
$(0.5,1)$	$(0.5,1)$	0	101.50	48.90	150.40
$(0.5,1)$	$(0.5,1)$	1	79.26	60.35	139.61
$(0.5,1)$	$(0.5,1)$	2	57.83	48.23	106.06
$(1,0.5)$	$(1,0.5)$	0	101.66	83.44	185.10
$(1,0.5)$	$(1,0.5)$	1	61.51	81.04	142.55
$(1,0.5)$	$(1,0.5)$	2	65.07	78.39	143.46

4. Conclusions and Future Work

Emission-based Production and Inventory Control System (EPICS) is insufficient to deal with the system's sustainable (reduced cost and emission without compromising service level) operational requirements. System emissions must be bought down with the decarbonization process or technological interventions, but acquiring these transitions will require a further delay. The role of the carbon market becomes necessary in such a situation where the short-term requirement for the system can be catered by this supply-demand driven market-mechanism. The above two sub-units (Technology transition module and Carbon Market module) with their individual challenges extended into EPICS (with their own challenge of using tunning parameters for better service level and system cost). This study simply proposes the existence of such a relationship between these sub-units. Some basic simulations are performed to highlight that a choice of better control parameter can significantly bring down system cost.

As a pathway, multiple directions are available to this study starting with model validation and calibration. A fictitious carbon market is introduced and integrated into this extension of EPICS, a more formal carbon market can be considered with varying (dynamic) carbon prices based on demand and supply. A better forecasting-based approach for clean technology transition with real data for empirical study can be used to determine system parameters. The choice of control parameters has a significant role in cost reduction, a relationship between control parameters, system cost, and service level can be explored for the sustainable production system.

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