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Integrating Ecological, Productive, and Macrofinancial Spheres with ESTEEM: A System Dynamics Framework to Assess Brazil's Transformation Plan

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Abstract

This paper presents a continuous-time behavioural ecological macroeconomic model grounded in the dynamic input–output (IO) framework, named ESTEEM, and applies it to the Brazilian economy. The model is calibrated using Brazil's IO matrix, and its primary goal is to serve as a policy and scenario-building toolbox, illustrated here through the Brazilian Economic Transformation Plan (Plano de Transformação Ecológica), announced at COP28 in 2023. Tailored for open developing economies, the model extends traditional IO analysis by integrating dynamic feedback loops, sectoral investment behaviour, inventory dynamics, wage and price formation, environmental pressures and constraints, and a range of policy instruments. Combining structuralist foundations with system dynamics, ESTEEM captures both short-term disequilibrium and long-term development paths, allowing simulations of industrial policy, fiscal and monetary interventions, structural change, and ecological transitions. Key innovations include the endogenisation of capital accumulation, adaptive expectations, and green technological change.

Keywords: Dynamic input-output, Ecological macroeconomics, Brazilian economy, Structuralism, Sustainable finance, Balance-of-Payment constraints, Green industrialization.

JEL codes: C63, C67, E12, O41, 044, Q57

1. Introduction

The Leontief input–output (IO) model has long been a cornerstone of structuralist economic analysis, providing a robust framework for tracing how changes in final demand propagate through intersectoral production networks. Widely used in planning and forecasting, the IO approach remains an important alternative for estimating macroeconomic and sectoral multipliers. However, in its traditional formulation, it is static, linear, and purely demand-driven, limiting its capacity to analyse behavioural responses, adjustment dynamics, and the complexity of real-world economic and environmental transitions.

This paper introduces ESTEEM, a dynamic structural ecological economic model build-up on the IO framework tailored to the specific conditions of open developing economies. Grounded in structuralist and ecological macroeconomics, the model integrates behavioural equations governing investment, capacity utilisation, price and wage formation, inventory dynamics, and trade performance. It also incorporates environmental feedbacks, such as sectoral emissions, land use, and resource intensity, allowing for explicit analysis of ecological transitions.

The model departs from conventional IO models by relaxing the assumption of instantaneous equilibrium. Firms form expectations, adjust production based on their inventories, and revise investment decisions according to profitability signals that unfold over continuous time. The model also simulates inflationary dynamics and external competitiveness by endogenising prices and markup features typically absent in quantity-focused Leontief models.

The motivation for this work is twofold. First, it responds to the need for policy-relevant macroeconomic tools that preserve the structural richness and sectoral resolution of IO models while incorporating dynamic adjustment and disequilibrium mechanisms. Second, it provides a simulation platform to evaluate Brazil's Plano de Transformação Ecológica (PTE), launched at COP28 in 2023. The PTE outlines an ambitious strategy for green reindustrialisation, technological upgrading, and regional development, combining short-term fiscal and financial incentives with long-term structural reforms in key sectors, including energy, transport, agroindustry, and bioeconomy.

This paper's core contribution is to demonstrate how ESTEEM can be used to assess the macroeconomic impacts of the PTE, particularly in terms of output growth, import substitution, employment generation, and environmental outcomes. By simulating alternative scenarios - such as targeted green investment, public procurement, R&D support, and domestic content policies - the model helps policymakers anticipate trade-offs, identify high-multiplier interventions, and design more coherent and effective strategies for inclusive, low-carbon development. In this sense, it serves not only as a modelling innovation but as a practical policy toolbox to support Brazil's structural transformation agenda.

The paper is organised as follows. Section 2 presents the theoretical foundations of ESTEEM, combining structuralist macroeconomics, ecological economics, and system dynamics to address the specific challenges of green structural change in developing economies. Section 3 reviews the literature on dynamic modelling approaches that integrate ecological constraints and behavioural dynamics within an input–output framework. Section 4 introduces the methodological structure of ESTEEM, outlining its behavioural blocks and formalising the system of differential equations that govern the model's dynamics. Section 5 demonstrates the applicability of the model to Brazil's Economic Transformation Plan (Plano de Transformação Ecológica), simulating a range of green industrial policy scenarios and evaluating their macroeconomic and environmental impacts. Section 6 concludes, highlighting the model's policy relevance and outlining avenues for future research.

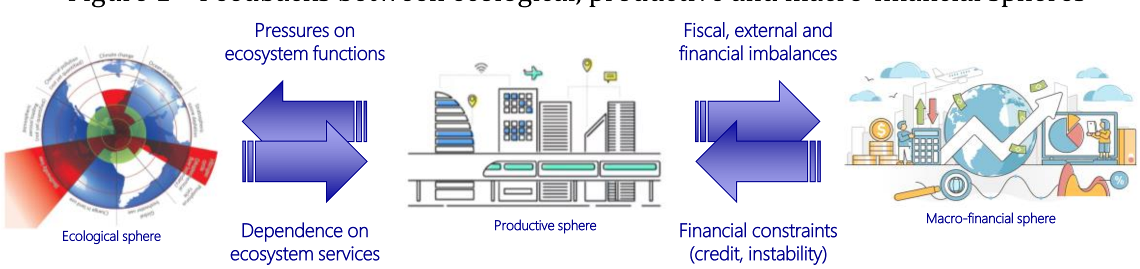
2. Theoretical Foundations

Built upon a rich tradition of structuralist economics (Ocampo, 2011), ecological macroeconomics (Hardj and O'Neill, 2017) and system dynamics (Sterman, 2000), ESTEEM captures the complex interplay between economic and environmental challenges faced by developing economies. Its theoretical underpinnings emphasise the importance of structural change, demand-led growth under binding constraints (external, fiscal, and socio-economic), and the centrality of environmental limits in shaping development trajectories.

Prior to its formalisation in this article, the foundational logic of the model was articulated by Magacho et al. (2023), whose work provides essential empirical motivation. The authors conceptualise the low-carbon transition as a specific type of rapid and disruptive structural change, one in which sunset industries (carbon-intensive sectors) decline and sunrise industries emerge, driven by policy, preferences, and technological change. Their analysis reveals that developing countries are macroeconomically exposed to this process through multiple dimensions: external dependency (foreign exchange from carbon-intensive exports), fiscal dependency (government revenues from fossil fuels and other carbon sectors), and socio-economic dependency (jobs and wages). This multi-dimensional exposure leads to heterogeneous vulnerabilities, shaped by countries' technological capabilities and the adaptability of their production structures. These empirical insights strongly justify the need for a multi-sectoral, system dynamics model, such as ESTEEM, capable of simulating how sectoral shifts, policy constraints, and environmental limits co-evolve over time.

Structural change is thus at the heart of the development process, particularly in the context of green transitions. Unlike the gradual, optimal reallocations assumed in mainstream models, structural change in the real world is typically unbalanced, path-dependent, and shock-driven. Countries with concentrated carbon-intensive export structures face non-linear and asymmetric risks in transitioning to a green economy (Mealy and Teytelboym, 2022). These findings underpin the choice of an input–output (IO) framework in ESTEEM, which allows detailed tracing of sectoral interdependencies and the propagation of economic and environmental shocks across production networks, as presented in Figure 1.

Figure 1 – Feedbacks between ecological, productive and macro-financial spheres



Autors' ellaboration

Ecological and productive spheres are connected through pressures and dependencies. On the one hand, productive dynamics put pressure on ecosystem functions by using natural resources and generating waste, pollution, and residuals. On the other hand, the productive sphere depends on ecosystem services to produce, and failures in supplying these services may constrain a country's capacity to supply goods and services.

From the lens of ecological economics, the model is grounded in the principle of strong sustainability (Yilmaz & Godin, 2024), rejecting the notion of *a priori* substitutability between natural and man-made capital. Natural resources – such as land, water, and carbon sinks – impose absolute biophysical limits on economic activity. Hence, ESTEEM adopts an IO production structure not only for inter-industrial linkages but also for ecological inputs and outcomes. Investment plays a transformative role, enabling technological upgrading and capacity expansion, but cannot substitute for depleted natural capital stocks. This echoes the observation that carbon pricing or efficiency gains alone are insufficient in contexts of high fiscal and socio-economic dependency, highlighting the need for integrated planning tools that consider irreversibility and constraint-driven dynamics.

The model also reflects the specific constraints of developing economies, as detailed in ECLAC's Three-Gap Model (Porcile et al., 2023) and Magacho et al. (2023). External vulnerabilities stem from reliance on a narrow export base, fiscal fragility is amplified by the decline of revenues from sunset industries, and socio-economic fragility is reflected in high informality, inequality, and weak social protection. These constraints are explicitly embedded in ESTEEM through mechanisms such as endogenous balance-of-payments constraints, credit rationing, and labour market frictions.

Unlike static IO approaches, ESTEEM introduces continuous-time disequilibrium dynamics for prices and quantities. Firms respond to demand fluctuations through inventory accumulation and production adjustments, allowing for temporary imbalances between supply and demand. The model includes price-setting mechanisms, where firms adjust markups in response to cost fluctuations and inventory deviations. It simulates adjustment paths under shocks to demand, investment, and natural capital, incorporating behavioural rules and policy feedback.

From a dynamic perspective, investment is the core of the ecological transformation. In the model, it is endogenously driven by profit expectations, capacity utilisation, and credit availability, generating cycles and transitions. Transition risks are path-dependent and multidimensional, requiring tools that can simulate out-of-equilibrium traverses, not just steady-state endpoints.

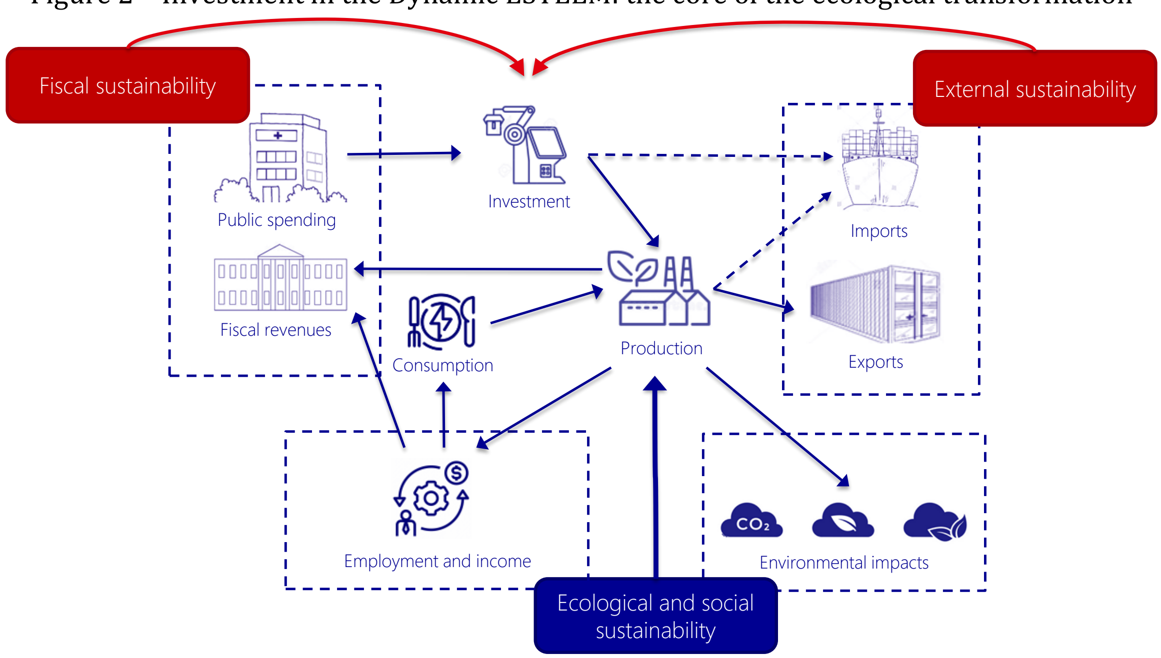
Labour dynamics incorporate structural unemployment and wage rigidities, consistent with Verdoorn-type productivity growth and Phillips-curve wage setting. These features allow the model to generate stylised facts such as jobless growth, inflationary spirals, or employmentled transformations, which are crucial for analysing the socio-economic dimensions of transitions on livelihoods.

Monetary policy is operationalised through a flexible generalised Taylor rule, adaptable to fixed or floating regimes, reflecting the monetary constraints of developing economies with limited monetary sovereignty. Exchange rates respond to inflation differentials and trade imbalances, endogenising the feedback between current account dynamics and macroeconomic instability.

Environmental dynamics in the model mirror the structure of hybrid IO models. Emissions, land use, and water consumption are linked to sectoral output via evolving environmental coefficients, capturing the co-evolution of structural change, environmental degradation and productive dependence on ecosystem services. This allows the simulation of decoupling scenarios and green investment trajectories, in line with policy concerns around balancing growth, resilience, and environmental goals.

The overall dynamics of how investment plays this transformative role and is a key variable connected to the macro-financial sphere are illustrated in Figure 2.

Figure 2 – Investment in the Dynamic ESTEEM: the core of the ecological transformation



Authors' elaboration

Public policies play a crucial role in transforming the economy by influencing investment decisions or executing these investments directly. By increasing profitability, for example, through subsidies on capital acquisition or sales, public policies can direct investments toward specific industries or technologies, thereby altering economic dynamics. On the one hand, these investments increase demand for machinery and equipment, buildings, software, and other capital goods, promoting an increase in production and productivity that may lead to higher competitiveness and an increase in exports. On the other hand, the high demand for these goods may lead to pressures on the current account balance, as capital goods and inputs are predominantly imported in developing countries (Tausch and Magacho, 2025). The external sustainability of a country therefore depends on its ability to produce these investment goods and inputs, and on how much these investments can boost exports.

Public direct investment and public policies to promote green investment are often costly for the government, implying fiscal expenditures. Nevertheless, increasing production and productivity lead to employment and income generation, which feed back into the economy through increased consumption. Sales, production, income, and consumption are taxed, and the increase in fiscal revenues may compensate for the initial expenses, depending on the capacity of these green investments to boost the economy and crowd in other investments (Mercure et al., 2019).

Beyond analysing the net impact of these fiscal and external imbalances on a static equilibrium model, it is essential to address the consequences of short-term disequilibria on macroeconomic variables that may constrain investment. This is where another crucial contribution of the dynamic traverse approach adopted by ESTEEM comes into play: investment is sensitive to interest rates, which, as discussed, depend on inflation. Because inflation in developing countries is driven, among other factors, by exchange rate devaluation, and interest rates may be impacted by fiscal imbalances, external and fiscal dynamics feed back into investment. This illustrates the importance of correctly incorporating macro-financial and productive dynamics into a model that seeks to address ecological transformation.

3. Literature Review

3.1. Integrating Ecological Economics and System Dynamics within an Input–Output Framework

A core question we address with ESTEEM is how to embed ecological and system dynamics within a macroeconomic input–output (IO) framework. Traditional Leontief IO models are static, linear, and purely demand-driven, assuming fixed technical coefficients and infinite supply elasticity. While effective for short-term policy analysis, these assumptions limit the ability of such models to capture real-world dynamics, behavioural adjustments, capacity constraints, and environmental feedbacks (Miller & Blair, 2009).

Attempts to overcome these limitations can be traced back to classical economists such as Harrod, Hicks, and Goodwin, who introduced the notion of economic "traverse" to study transitions between growth equilibria. Their work emphasised disequilibrium phenomena -

such as bottlenecks, cycles, and persistent underemployment - that mainstream macroeconomic models tend to neglect. More recent modelling approaches, including system dynamics, stock–flow consistent (SFC) models, and agent-based models (ABM), have placed adjustment processes and feedback mechanisms at the centre of macroeconomic analysis.

System dynamics, in particular, provides tools to model feedback loops, stock–flow relations, and time lags - features essential for integrating ecological constraints into economic analysis. Early contributions, such as Metzler (1941), illustrated how inventory cycles in Keynesian settings can produce endogenous demand fluctuations, anticipating the central concerns of system dynamics. A landmark application of this approach was The Limits to Growth study (Meadows et al., 1972; 2004), which modelled the interaction between economic growth and planetary boundaries. It introduced the concept of "overshoot and collapse," highlighting nonlinear feedbacks, threshold effects, and the risks of surpassing ecological limits.

This modelling tradition supports the principle of strong sustainability, which argues that natural capital (e.g., ecosystems, carbon sinks) is not substitutable by physical or human capital. Once critical thresholds are crossed, damage may become irreversible (Neumayer, 2010; Daly, 1996). This contrasts with the weak sustainability view (Solow, 1974), which assumes substitutability between capital factors. In the context of IO models, strong sustainability implies Leontief-like constraints: when critical inputs such as clean water, land, or carbon space are depleted, economic output cannot continue. ESTEEM incorporates this through emissions coefficients and natural resource limits, which explicitly restrict the growth path.

Environmentally extended input–output (EEIO) analysis builds on the traditional IO framework by including data on emissions, wastes and resource use to evaluate the environmental footprint of sectors (Leontief, 1970; Wiedmann & Lenzen, 2018). This enables both production- and consumption-based accounting of emissions (Peters, 2008), which is crucial for understanding global trade's role in shifting environmental burdens. However, despite its value for footprint analysis and policy design, EEIO remains static and lacks behavioural or feedback dynamics.

To overcome these limits, some models combine IO analysis with system dynamics. Moffatt and Hanley (2001), for example, developed two integrated models for the Scottish economy: one using system dynamics to capture long-run trends and another using EEIO to analyse sectoral impacts. Their work highlights the complementarity of IO detail with dynamic feedback mechanisms in designing policies that are both sector-specific and system-aware. ESTEEM merges these approaches in a continuous-time IO macro framework. By expressing IO relations as differential equations, it models time-based behaviour, capturing stocks, delays, and feedbacks, while keeping sectoral richness. Dynamic IO modelling has deep roots. Leontief (1953) proposed a dynamic version linking investment to capacity, but early models faced technical limits. Interest has revived for applications like disaster impact, energy transitions, and value chains (Galbusera & Giannopoulos, 2018).

Continuous-time disequilibrium macro models offer further tools. Achdou et al. (2022) use partial differential equations to model heterogeneous agents with constraints and smooth dynamics. Similarly, ESTEEM allows flexible adjustment speeds (e.g. for prices or emissions) without arbitrary time steps. Climate-economy system dynamics models have also advanced. Fiddaman's (2002) FREE model incorporates expectations and feedbacks, showing that delayed policy raises transition costs. Mercure et al. (2019) find that non-equilibrium models often predict positive green investment impacts under slack, unlike CGE models that assume full employment and predict losses.

These differences stem from assumptions: equilibrium models assume neutral money and full capacity use, while non-equilibrium models allow idle resources and credit to fuel green growth. ESTEEM aligns with the latter, combining demand-led growth, endogenous investment, and environmental limits. Recent studies also highlight cascading effects and network risks. Cahen-Fourot et al. (2021) show that decarbonisation can strand assets and disrupt supply chains. Seppecher et al. (2018) find that markup changes and firm heterogeneity create inflation and output volatility during transitions. These findings stress the need for models that account for price dynamics, firm behaviour, and path dependence. ESTEEM includes disequilibrium price adjustments: firms change prices based on costs (wages, imports, carbon taxes) and imbalances, allowing for simulations of greenflation and transition frictions (bottlenecks, skill gaps, financial limits).

In sum, ESTEEM unifies sectoral detail with behavioural and ecological feedbacks. Static IO models show intersectoral multipliers but miss dynamics; system dynamics simulate transitions but lack sectoral depth. ESTEEM combines both, offering a robust tool for analysing green structural change in constrained developing economies. It represents a structuralist system dynamics approach to ecological macroeconomics, integrating IO realism, dynamic feedbacks, and environmental limits, crucial for assessing sustainable transformation under multiple constraints.

3.2. Macroeconomic Challenges and Opportunities in Brazil's Green Transformation

A central research question addressed here is how dynamic structural macroeconomic modelling can be used to assess the macroeconomic impacts of green transition policies—particularly in developing countries. One relevant case is Brazil's Ecological Transformation Plan (PTE, in Portuguese), launched in 2023, which seeks to decarbonise the economy while promoting economic growth through investments in renewable energy, green industry, and employment generation. The PTE marks a return to industrial policy with social and ecological objectives at its core.

Green industrial policy holds the potential to deliver a "triple dividend": economic growth, environmental sustainability, and social inclusion. However, this potential comes with trade-offs. Key policy questions emerge: will technology imports worsen Brazil's external balance?

Can green growth reduce inequality? Will the transition create sufficient quality jobs, and for whom?

Conventional tools like static input–output (IO) or computable general equilibrium (CGE) models offer limited insights into these dynamic trade-offs. Static IO models can estimate green investment multipliers, typically showing that renewable sectors create more jobs per dollar and depend less on imports than fossil sectors (Bowen et al., 2018; Garrett-Peltier, 2017). However, green transitions also shift labour demand toward higher-skilled jobs, often generating short-term labour shortages (Chen et al., 2020). In contrast, dynamic models can endogenise these constraints and simulate adjustments in labour markets and wages over time (Magacho & Spinola, 2025).

Structural change is a key channel through which green industrial policies generate broader impacts. Marconi et al. (2016) argue that manufacturing-led green growth can stimulate services and innovation through inter-sectoral linkages. Brazil's PTE targets domestic production in sectors like solar panels, batteries, and green hydrogen—areas aligned with this developmental vision. ESTEEM allows for the simulation of various scenarios based on the pace of technological adoption and structural transformation.

Financing the transition poses another challenge. The PTE relies heavily on public investment, which can be expansionary in underutilised economies (Zezza & Godin, 2012), but risks creating inflationary pressures or fiscal strain in contexts of tight labour markets or supply-side bottlenecks. Monetary–fiscal coordination is therefore essential. Campiglio (2016) proposes that central banks and development banks adopt green credit policies to support low-carbon investment. ESTEEM enables exploration of alternative monetary regimes and their consequences for inflation, investment, and green outcomes—critical for inflation-sensitive economies like Brazil (Jackson & Jackson, 2023).

Distributional effects are also at the forefront. Without compensatory policies, carbon taxes, subsidy reforms, and green investments can be regressive. Moz-Christofoletti and Pereda (2021) show that redistributing carbon tax revenues can enhance progressivity. Employment effects must also be considered: while green sectors may create jobs, polluting sectors may lose them. Inter-sectoral modelling is required to simulate these employment dynamics and assess whether job losses can be mitigated through retraining, income support, or targeted investment.

Input–output models offer a useful basis for such sectoral analysis. Bastidas and McIsaac (2019) demonstrate that Brazil could meet its Nationally Determined Contributions (NDCs) by shifting toward service sectors, reducing imports, and increasing revenues—though average wages may fall. Dynamic models, like ESTEEM, can investigate whether these patterns are driven by structural change, labour market frictions, or both, and can test alternative policy interventions. Technology and finance emerge as key levers for a successful green transition. Gramkow and Porcile (2022) emphasise the role of technological progress and international support in achieving growth, decarbonisation, and external balance simultaneously. ESTEEM allows for scenario analysis involving export-led strategies and concessional finance.

Sectoral priorities also shape transition outcomes. Marconi et al. (2016) caution against relying on commodity exports and advocate for green industrialisation in sectors with high multipliers—such as electric vehicles, green manufacturing, and agri-tech. ESTEEM enables comparative assessment of these sectoral pathways. Given that employment is central to the PTE's political and economic viability, modelling can help determine when and where green jobs emerge relative to fossil phase-outs, and whether complementary policies (e.g., retraining) are needed.

Environmental metrics must be integrated alongside economic indicators. Ecological macroeconomics calls for tracking carbon intensity, resource efficiency, and sustainability indicators alongside GDP (Jackson, 2017). Policy sequencing also matters: poorly coordinated interventions can increase macroeconomic volatility (Yanovski et al., 2024). ESTEEM explicitly tracks ecological and economic trade-offs and can simulate risks such as stranded assets, inflation shocks, and climate-induced events. Mercure et al. (2021) recommend evaluating climate policy using a risk-based approach—something dynamic models are particularly suited for.

We advocate that green transitions in the Global South require integrated dynamic modelling frameworks to capture macroeconomic, structural, and ecological interdependencies. Static or aggregate models often miss key dynamics, such as adjustment processes, bottlenecks, and distributional outcomes. ESTEEM offers a flexible, structuralist, and ecologically informed tool to simulate Brazil's green transition on a year-by-year basis. In doing so, it contributes to a growing literature on dynamic, disequilibrium modelling of green development in the Global South (Mercure et al., 2019; Cahen-Fourot et al., 2020; Jackson & Jackson, 2023).

3.3. Structuralist Macroeconomic Modelling

A key challenge in dynamic macroeconomic modelling is how to represent structural transformation in open developing economies facing binding external, fiscal, and environmental constraints. Structuralist macroeconomics addresses this by emphasising the distinct characteristics of developing economies, such as demand-led growth, production structure, and persistent supply-side bottlenecks (Ocampo, 2011; Lavoie, 2014). Unlike neoclassical models, structuralist frameworks reject the assumption of smooth adjustment and factor substitutability, focusing instead on constraints such as the balance of payments, which often limit growth to socially undesirable levels (Thirlwall, 1979). These economies also exhibit dualism, characterised by a modern sector with higher productivity and a large traditional sector, which creates underemployment and low-growth traps unless resources are shifted toward more productive activities. Formal models by Ocampo and others incorporate such dual economies with multiple equilibria, where modern-sector growth depends on demand (especially investment) and capacity utilisation. Yet, external and labour market constraints can stall transformation.

External dependency is central. Latin American structuralists (e.g. Prebisch, Furtado) highlighted the growth limits imposed by primary export dependence and import-intensive industrialisation. Neostructuralist extensions, such as the "three-gap" model, integrate external, fiscal, and environmental limits. Gramkow and Porcile (2022) identify three growth thresholds: (1) consistent with external balance, (2) necessary for poverty reduction, and (3) compatible with climate targets. Their findings show these thresholds are misaligned—growth rates required for social inclusion exceed those allowed by external and environmental constraints. This triple challenge—structural change, external balance, and decarbonisation—underscores the need for integrated macroeconomic-environmental models that reflect real-world constraints.

Fiscal space and financing capacity form another key barrier. Public investment is essential for development and green transitions, yet many developing countries cannot finance needed investments through sustainable deficits or aid. Structuralist models (Taylor, 2004; Ocampo et al., 2009; Botta et al., 2024) account for this fiscal gap, advocating counter-cyclical policy to stabilise demand and industrial policy to address supply bottlenecks. Both are complementary: the former manages shocks; the latter fosters long-term transformation.

The green transition adds urgency and complexity. It requires reallocating resources from carbon-intensive to green sectors—akin to traditional structural change but now environmentally driven. Marconi et al. (2016), for example, show that Brazil's commodity-based growth yields weak intersectoral linkages, while manufacturing stimulates broader economic activity. Thus, green reindustrialisation—e.g. renewable energy equipment, electric vehicles—offers a path to both growth and sustainability. Conversely, continued reliance on fossil fuels or low-value agriculture risks low-growth traps and climate inaction.

Socio-economic dualism also constrains inclusive transitions. Without robust job creation, surplus labour remains in the informal sector. Structuralist models (Rada, 2007; Ocampo et al., 2009) show that unless modern-sector growth is strong and inclusive, dualism persists. Green policies must therefore ensure a just transition, where job creation and equity are central. Studies like Bastidas and McIsaac (2019) suggest Brazil could reduce emissions while increasing employment by shifting demand toward services and renewables. However, they also warn of potential wage pressure, reinforcing the need for complementary policies to guide equitable structural change.

4. ESTEEM

ESTEEM is a continuous-time, multi-sectoral system dynamics model that extends the classical Leontief input–output framework into a behavioural, nonlinear, and disequilibrium context. It is designed to simulate transitional macroeconomic dynamics in open developing economies, where structural change, policy shocks, and environmental feedback play a critical role.

The model builds directly upon recent advances in disequilibrium input–output modelling, particularly the traverse framework introduced by Spinola and Magacho (2025). In contrast to traditional static Leontief models that assume immediate equilibrium between supply and demand, the traverse approach recognises that economic systems undergo gradual adjustments in both quantities and prices. In the model by Spinola and Magacho (2025), sectoral production adjusts continuously in response to demand fluctuations through inventory dynamics. At the same time, prices evolve based on cost-push mechanisms and markup-setting behaviour. Building from this foundation, ESTEEM extends the analysis by introducing endogenous investment dynamics, environmental feedback, and a full macroeconomic closure tailored to the constraints of developing economies.

Investment behaviour in ESTEEM is modelled as a dynamic process driven by profitability expectations and credit conditions, departing from fixed capital coefficients. This extension allows us to capture how sectoral accumulation processes evolve, influencing both productive capabilities and environmental impacts. The treatment of employment and wages also reflects the disequilibrium structure. Labour demand is determined by sectoral output and productivity, while wage dynamics follow a Phillips-curve-like mechanism, linking wage growth to labour market tightness, productivity trends, and inflation expectations. Endogenous productivity growth is modelled through a Verdoorn-type relationship, whereby sectors experiencing higher output growth gradually enhance their labour productivity.

Monetary policy is represented through a generalised Taylor rule framework, where central banks adjust interest rates in response to inflation deviations and output gaps. Depending on country-specific characteristics, the model can accommodate flexible inflation targeting regimes or fixed exchange rate arrangements, allowing the analysis of different macroeconomic contexts. In either case, monetary dynamics interact with credit conditions and investment decisions, shaping the economy's adjustment path.

Environmental dynamics are explicitly integrated into the model structure. Emissions arise from multiple sources - including industrial activities, energy use, and land-use change - and evolve endogenously with sectoral production patterns and technological upgrading. Natural resource use, including land and water, is captured through environmental input–output coefficients, which evolve as sectors invest in cleaner technologies or shift toward greener production processes.

4.1. Foundations in Leontief Input–Output Modelling

The technical coefficients matrix **A** is the backbone of the model's production system. It determines the quantity of input from each sector required to produce one unit of output in every other sector. Final output in each sector i is partially constrained by the technological input requirements from other sectors, ensuring that the technical structure of the economy remains coherent. The domestic demand identity follows the standard decomposition:

$$\mathbf{Y^A} = \mathbf{AY} + \mathbf{C} + \mathbf{I^K} + \mathbf{G} \quad (1)$$

Where $\mathbf{Y^A}$ is the absorption vector (total domestic use); $\mathbf{AY}$ represent Intermediate inputs, and $\mathbf{C}, \mathbf{I^K}, \mathbf{G}$ are the domestic final demand components (household consumption, fixed investment, government expenditure). This captures the circular flow of production. In ESTEEM, this structure remains intact but is enriched by feedback dynamics that govern how final demand evolves.

In a traditional IO model, final demand is exogenous, and output adjusts linearly via the Leontief inverse. ESTEEM replaces this with behavioural equations for household consumption, government expenditure, fixed capital investment, and trade flows. These components evolve in continuous time, influenced by policy, prices, income distribution, and external shocks. Therefore, output becomes a state variable governed by differential equations rather than matrix multiplication alone. This transition turns the model into a system dynamics engine grounded in empirical IO coefficients.

Because all real economy flows (production, employment, emissions, etc.) are organised by sector, any shock (whether in demand, prices, productivity, or policy) propagates through the intersectoral matrix. For example: a demand shock in food raises output in agriculture, services, and transport. A carbon tax on energy raises production costs across all sectors, depending on their energy intensity. Thus, structural interdependencies shape the speed, direction, and magnitude of adjustment. This is a key improvement over aggregate macro models, which miss sector-specific feedback loops. Firms form prices based on costs (labour, intermediate inputs, and environmental). The IO matrix therefore determines not only production requirements, but also price transmission—i.e., how a change in the price of one sector (e.g., oil) affects all others via input costs. This allows the model to simulate cost-push inflation, green inflation, and sectoral cost heterogeneity.

The model advances beyond standard IO by endogenising value added, income distribution, and dynamic stocks. Gross value added (GVA) is computed by sector as the difference between total output and intermediate use. It is then allocated across wages (labour income), profits (capital income), and taxes/subsidies. These components directly influence household consumption (through income), government revenues (through taxation), and investment decisions (via profitability), thus capturing the functional distribution of income as an endogenous outcome rather than an exogenous assumption. In parallel, the model incorporates key stock variables, including inventories to manage short-term supply-demand imbalances, capital stock evolving with investment and depreciation, and productivity improving through output growth and green technological learning. These elements are continuously updated, creating feedback loops that influence production costs, emissions, and macroeconomic trajectories.

The model departs from equilibrium assumptions and allows for the accumulation of imbalances over time. Each behavioural block - investment, consumption, trade, labour, prices, government, and environment - is defined by a differential equation that captures the adjustment process. This structure allows the system to traverse disequilibrium states, incorporating delays, expectations, and non-linearities.

The full model is represented as a differential-algebraic system (DAE) which is structurally simplified to an ordinary differential equation (ODE) system. The next subsections formally present the model's structure and dynamic equations, detailing the key behavioural mechanisms and feedbacks that drive the system's evolution.

4.2. Capital accumulation and Investment

For the productive capacity and capital stock, each sector has a productive capacity denoted by the vector $\mathbf{Y^P}$. Given its current capital stock, this represents the output the sector can produce at a normal capacity utilization level. Productive capacity is not fixed - it evolves depending on the sector's investment decisions. The growth of productive capacity is described by:

$$\dot{\mathbf{Y}^{\mathbf{P}}} = \beta^{K}(\mathbf{Y^T} - \mathbf{Y^P}) \tag{2}$$

and

$$\dot{\mathbf{Y}^{\mathbf{T}}} = \widehat{\mathbf{Y^T}}\widehat{\boldsymbol{\psi}^{\mathbf{u}}}[\mathbf{g^e} + \hat{\boldsymbol{\gamma}}^{\mathbf{r}}(\mathbf{r^e} - \mathbf{i^L})] \tag{3}$$

Sectoral change in effective capacity is a continuous process governed by a target capacity, where β^K is an adjustment speed that determines the time needed for this adjustment. Sectoral change in target capacity is endogenously determined by firm expectations and profitability. The core of the investment decision lies in how firms determine their target capacity. In ESTEEM, this is not an arbitrary assumption or exogenous input, but a non-linear behavioural function based on expected profitability of capital, interest rates (cost of borrowing), expectations of demand growth, and capacity utilisation pressure. In this equation, $\boldsymbol{\gamma}^{\mathbf{r}}$ is the sensitivity of target growth to profitability. $\mathbf{i^L}$ represents the lending interest rate for the sector. Also, $\mathbf{g^e}$ is the expected demand growth. $\boldsymbol{\psi}^{\mathbf{u}}$ is a hyperbolic function set to one, but it goes to zero when capacity utilisation is very low.[1]

[1] In this formulation, there is no inferior limit for capital accumulation, and it might be inferior to the depreciation rate. We can represent this save equation in a continuous way as:

$$\left(\frac{1}{k}\ln\left(1 + e^{k\left(\mathbf{g^e} + \hat{\boldsymbol{\gamma}}^{\mathbf{r}}\left(\mathbf{r^e} - \mathbf{i^L}\right) + \delta_i\right)}\right)\right) - \delta_i$$

The expression inside the ln-exp formulation represents a smoothed version of a threshold function (soft maximum), which activates investment only when borrowing costs sufficiently exceeds expected profitability.

When expected returns are higher than borrowing costs and utilisation is high, capital accumulation increases non-linearly. This reflects the real-world tendency of firms to invest more aggressively in high-demand, high-return environments, and conversely to slow investment in downturns. This equation makes the model sensitive to the business cycle and captures asymmetry between booms and recessions.

Investment in fixed capital in each sector, denoted by $\mathbf{I^K}$, is composed of two parts: replacement investment, which offsets capital depreciation and expansionary investment, which adds to the capital stock:

$$\mathbf{I^K} = \hat{\boldsymbol{\delta}}\mathbf{B}\mathbf{Y^P} + \mathbf{B}\dot{\mathbf{Y}}^{\mathbf{P}} \tag{4}$$

In which $\boldsymbol{\delta}$ is the sectoral depreciation rate vector, $\mathbf{B}$ is the capital-use matrix, and $\mathbf{Y^P}$ is the current productive capacity. The first term maintains existing capacity by replacing worn-out capital. The second term adds new capital to increase future capacity.

Incremental expected profitability, $\mathbf{r^e}$**,** is the key signal that firms use to decide whether investment is worthwhile. It is defined as the expected gross return over cost, normalised by the price of capital goods:

$$\mathbf{r^e} = \left(\mathbf{p^b} - \mathbf{UC}\right) \oslash \left(\mathbf{B}'\mathbf{p^f}\right) \tag{5}$$

Where $\mathbf{p^b}$ is the expected output price before taxes (basic price) of the sector's good. **UC** is the unit cost of production, which includes wages, intermediate inputs, and carbon taxes. $\mathbf{B}'\mathbf{p^f}$ represents the price of capital goods, i.e. the cost of investing in new machinery or infrastructure.

The term $\boldsymbol{\psi}^{\mathbf{u}}$ provides a lower bound for target capital accumulation based on expected capacity utilization. It is defined as:

$$\boldsymbol{\psi}^{\mathbf{u}} = \frac{1}{2}\left[1 + tanh\left(50(\mathbf{u^e} - 0.85)\right)\right] \tag{6}$$

where $\mathbf{u} = \left(\widehat{\mathbf{Y^P}}\right)^{-\mathbf{1}}\mathbf{Y^e}$ is the expected capacity utilisation rate ($\mathbf{Y^e}$ is the expected demand). When $u_i < 0.85$, firms are reluctant to invest even if profits are high. When $u_i > 0.85$, it rises quickly and approximates to one. Thus, the model avoids unrealistic over-investment in idle sectors and channels investment toward sectors under pressure.

Finally, expected growth is a time-adjustment process to expected demand governed by the adjustment speed (β^g):

$$\dot{\mathbf{g}}^{\mathbf{e}} = \beta^g[\left(\widehat{\mathbf{Y^e}}\right)^{-\mathbf{1}}\dot{\mathbf{Y}}^{\mathbf{e}} - \mathbf{g^e}) \tag{7}$$

This formulation embeds several critical assumptions. First, price expectations matter: firms make forward-looking decisions based on anticipated market conditions. Second, relative profitability is more important than absolute profitability - what drives investment is not the price level itself, but how it compares to production costs. When expected unit profits are low or negative, firms are likely to reduce or postpone investment.

4.3. Output, Demand, and Inventory

In traditional Leontief models, output is strictly demand-driven and computed as a static solution to a linear system. In contrast, we adopt a disequilibrium approach where output is determined dynamically, adapting to expected demand and inventory changes. This formulation captures the short-term frictions and adaptive behaviours found in real-world production systems, particularly in developing economies.

This block explains how firms decide how much to produce, how much to store, and how to adjust expectations when actual demand deviates from anticipated trends.

The actual output, denoted $\mathbf{Y}$, is a convex combination of two elements:

$$\mathbf{Y} = \widehat{\mathbf{\Omega}}\mathbf{Y}^{\mathbf{P}} + (\mathbf{I} - \widehat{\mathbf{\Omega}})(\mathbf{Y}^{\mathbf{e}} + \mathbf{V}^{\mathbf{d}} - \mathbf{V}) \quad (8)$$

Where $\Omega_i \in [0,1]$ is a capacity constraint index, determining the weight given to the supply-side constraint (Ω_i = 1 is set for the commodity producers and Ω_i = 0 for the others), $\mathbf{V}^{\mathbf{d}}$ is the desired inventory level and. $\mathbf{V}$ is the current inventory. If $\Omega_i \rightarrow 1$, the output is fully supply-constrained, i.e., the sector operates at full capacity. If $\Omega_i \rightarrow 0$, the output is fully demand-driven, adjusted based on expected sales and the need to replenish or reduce inventories. Depending on context, this structure allows the model to switch between Keynesian (demand-led) and classical (supply-constrained) regimes.

Firms operate under uncertainty and do not possess perfect foresight. Instead, they form expectations about future demand based on past experiences and revise them progressively as new information becomes available. This learning process is captured by a differential equation that models adaptive adjustment, ensuring that firms update their sales expectations in response to observed discrepancies between actual and expected demand over time:

$$\dot{\mathbf{Y}}^{\mathbf{e}} = \beta^{y} (\mathbf{Y}^{\mathbf{D}} - \mathbf{Y}^{\mathbf{e}}) + \widehat{\mathbf{Y}}^{\mathbf{e}}\mathbf{g}^{\mathbf{e}} \quad (9)$$

where $\mathbf{Y}^{\mathbf{D}}$ is the vector of actual demand and β^{y} is a speed of adjustment parameter.

If actual demand exceeds expectations, firms revise their expectations upward. If actual demand falls short, they become more pessimistic. Expectations also grow organically with trend expectations $\mathbf{g}^{\mathbf{e}}$, such as long-run growth plans. This kind of adaptive expectations mechanism introduces inertia into firm behaviour, making the system dynamically stable while still responsive to shocks.

Inventories $\mathbf{V}$ serve as a buffer between production and demand ($\dot{\mathbf{V}} = \mathbf{Y} - \mathbf{Y}^{\mathbf{D}}$). In this model, inventories evolve endogenously:

$$\dot{\mathbf{V}} = \frac{1}{k} \ln\left(1 + e^{k(\mathbf{Y} - \mathbf{Y}^{\mathbf{D}} + \mathbf{V})}\right) - \mathbf{V} \quad (10)$$

This is a smooth, bounded adjustment function where $\mathrm{Y} - \mathrm{Y}^{\mathrm{D}}$ is the net supply surplus or shortage. $\mathbf{V}$ is the current stock. This functional form avoids discontinuities. It behaves like a logistic function: when supply exceeds demand, inventories accumulate, when demand exceeds supply, inventories deplete (constrained to a zero-lower bound). It ensures inventories adjust gradually, mimicking real-world stock management.

When production exceeds current demand, unsold goods accumulate as inventories. In response, firms will likely scale back future production to avoid overstocking. Conversely, inventories are drawn down when demand outpaces supply, prompting firms to increase output to meet anticipated needs. In this way, inventories play a stabilising role in the economy, acting as a buffer that smooths fluctuations in production and helps mitigate abrupt changes in output. In capital accumulation, inventory levels directly influence firms' perceived profitability and, by extension, their investment decisions and price-setting behaviour. When inventories rise, indicating unsold stock, firms may reduce output or lower prices to clear the excess supply. In trade, higher inventories increase the share of output available for export, while low inventories may constrain foreign sales. From a price formation perspective, excess inventories put downward pressure on prices as firms seek to stimulate demand, whereas depleted inventories may support price increases. More broadly, inventories enable the model to accommodate transitory disequilibrium: output can temporarily exceed or fall short of demand without triggering systemic instability. This buffer mechanism allows for a more realistic adjustment path, where production expectations and output gradually align through adaptive behaviour, rather than through instantaneous market clearing.

4.4. External Sector

The model implements a dual export mechanism that captures two distinct but complementary logics. In sectors dominated by commodities or natural resources, exports are primarily supply-driven, functioning as the residual of total output and domestic absorption (including imports). These sectors are typically price takers in international markets. In contrast, exports follow a competitiveness-driven function for manufacturing and technologically dynamic sectors based on a multiplicative formulation that integrates both price competitiveness (relative domestic vs. foreign prices adjusted for exchange rates and tariffs) and non-price competitiveness (captured by sectoral productivity and learning effects). This flexible structure enables the model to simulate a wide range of trade configurations and assess the structural effects of changes in global conditions or national policy.

$$\mathbf{X} = \widehat{\boldsymbol{\Omega}}(\mathbf{Y} - \mathbf{Y^A} + \mathbf{IM}) + \left(\mathbf{I} - \widehat{\boldsymbol{\Omega}}\right)\widehat{\boldsymbol{\zeta}^{\mathbf{X}}}\left(\widehat{\mathbf{p^b}}\left(1 + \mathbf{t^Y}\right) \oslash (\mathbf{p^w} e^N)\right)^{\boldsymbol{\eta}^{\mathbf{x}}} \quad (11)$$

In which $\mathbf{X}$ are the exports vector, and $\mathbf{IM}$ is the vector of imports (i.e. what's added to meet absorption). $\boldsymbol{\zeta}^{\mathbf{X}}$ is the export propensity, $\mathbf{p^w}$ is the world price vector. e^N is the nominal exchange rate (local per foreign), $\mathbf{t^Y}$ is the export tariff vector and $\boldsymbol{\eta}^{\mathbf{x}}$ is the price elasticity of exports.

The first term reflects a supply-side logic, exports are the residual after domestic needs are met. The second term reflects a price competitiveness mechanism: exports increase when domestic goods are cheaper than world prices (adjusted for tariffs and exchange rates). This dual formulation allows the model to capture both export capacity constraints and price-driven trade dynamics, which are crucial in policy simulations like currency devaluations, trade liberalisation, or export subsidies.

Export propensity (ζ^X) evolves as follows:

$$\dot{\boldsymbol{\zeta}^{\mathbf{X}}} = \widehat{\boldsymbol{\zeta}^{\mathbf{X}}}\left[\mathbf{g^w} + \varepsilon^x(\hat{\mathbf{a}}^{-\mathbf{1}}\dot{\mathbf{a}} - \boldsymbol{\alpha}^{\mathbf{a}})\right] \quad (12)$$

where $\mathbf{g^w}$ is the growth rate of world sectoral demand, $\mathbf{a}$ is the domestic sectoral productivity, $\boldsymbol{\alpha}^{\mathbf{a}}$ is the sectoral world productivity growth and ε^x is the sensitivity of the export propensity to productivity differential that is not incorporated in prices (non-price competitiveness parameter).

Imports $\mathbf{IM}$ are determined by the import propensity. Imports are determined as a function of domestic demand:

$$\mathbf{IM} = \widehat{\boldsymbol{\sigma}^{\mathbf{M}}}\mathbf{Y^A} \quad (13)$$

where $\boldsymbol{\sigma}^{\mathbf{M}}$ is the import propensity vector.

This means that as the economy grows and absorbs more, it imports more, unless the production structure or relative prices change. Import propensity is determined by a typical multiplicative function that accounts for price competitiveness:

$$\boldsymbol{\sigma}^{\mathbf{M}} = \boldsymbol{\zeta}^{\mathbf{M}}\left((\widehat{\mathbf{p^w}} e^N)\left(1 + \mathbf{t^M}\right) \oslash \mathbf{p^b}\right)^{\boldsymbol{\eta}^{\mathbf{M}}} \quad (14)$$

Where $\boldsymbol{\zeta}^{\mathbf{M}}$ is the underlying import propensity (can change with learning or policy). $\mathbf{t^M}$is the import tariff. $\boldsymbol{\eta}^{\mathbf{M}}$ is the price elasticity of imports.

If foreign goods become more expensive relative to domestic goods (e.g. through a depreciation or tariff increase), import intensity falls. If foreign goods are cheap, sectors rely more on imports, often for critical intermediate inputs. Endogeneity of $\boldsymbol{\sigma}^{\mathbf{M}}$ is a key innovation, allowing the model to analyse import substitution dynamics, terms-of-trade shocks, and Structural trade dependence.

Although not fully detailed above, the model includes additional differential equations that allow export propensity to grow with productivity, learning, and import propensity to change if domestic capabilities improve. These mechanisms link trade dynamics to technological progress and industrial policy, making the model suitable for exploring questions of trade diversification, premature deindustrialisation, and structural transformation.

4.5. Consumption and Income Distribution

Households do not instantly adjust their consumption to changes in income or prices. Instead, they adapt gradually, reflecting inertia in preferences, habits, and expectations:

$$\dot{\mathbf{C}} = \beta^{c} \left(\mathbf{C}^{\mathbf{T}} - \mathbf{C}\right) \tag{15}$$

Where $\mathbf{C}$ is the vector of actual consumption of goods and services. $\mathbf{C}^{\mathbf{T}}$ is the target consumption level. β^{c} is the speed of adjustment (how fast households respond to changes). If actual consumption is below (above) the target level, it increases (decreases) over time. The parameter β^{c} controls how quickly these adjustments happen. This structure introduces stability into the system and allows for realistic lagged responses to shocks (e.g., a tax increase or wage cut won't immediately crash consumption).

The target level of consumption $\mathbf{C}^{\mathbf{T}}$ is derived from two components: autonomous consumption, driven by public transfers and base consumption, and induced consumption, based on household income (wages and profits) and relative prices.

$$\mathbf{C}^{\mathbf{T}} = \left[\mathbf{c_0}\, ST + \left(\mathbf{c}_{\mathbf{1}}^{\mathbf{W}} W \;+\; \mathbf{c}_{\mathbf{1}}^{\mathbf{P}} \Pi\right) \left(\frac{\mathbf{p^f}}{p^{c}}\right)^{\boldsymbol{\eta}}\right] \oslash \mathbf{p^f} \tag{16}$$

Where $\mathbf{c_0}$ is the propensity to consume from transfers. ST are total social transfers (e.g. pensions, subsidies). $\mathbf{c}_{\mathbf{1}}^{\mathbf{W}}$, $\mathbf{c}_{\mathbf{1}}^{\mathbf{P}}$ are the propensity to consume from wages and profits, respectively. W is wage income. Π is profit income. $\mathbf{p^f}$ is the vector of final price of good*s*, p^{C} is the consumer price index (CPI) and $\boldsymbol{\eta}$ is the vector of price elasticity of demand.

Households allocate their income across consumption goods depending on the relative price of each good – when $\mathbf{p^f}\,/p^{C}$ increases (i.e., good i becomes more expensive), its demand falls - capturing basic consumer behaviour. By including this term, the model introduces relative price sensitivity. If good i as the sector becomes more expensive relative to the consumer basket, its real demand falls. If prices fall, demand rises, increasing the sector’s contribution to total output. This formulation enables policy simulations involving Inflation scenarios (especially food and energy), Consumption taxes (e.g., carbon taxes), subsidies, and price controls.

The variable ST (social transfers) ensures minimum consumption levels for vulnerable households. It provides an automatic fiscal stabiliser: when output or employment fall, transfers can rise (depending on government rules). It interacts with the fiscal block, linking social policy to macroeconomic stability. In developing economies where large shares of the population have low or unstable income, this mechanism allows the model to simulate poverty alleviation, universal basic income, or social safety net policies.

The model divides national income between Labour (W) and Capital (Π). These components influence consumption differently: wage income W is typically associated with higher consumption propensities, especially for lower-income households. Profit income Π, in contrast, may be saved or reinvested at a higher rate.

Wage bill (W) and profits (Π) are:

$$W = \mathbf{w}'\mathbf{n} \tag{17}$$

$$\Pi = \mathbf{GOS}'(1 - \boldsymbol{\sigma}^{\mathbf{G}}) \tag{18}$$

where Gross Operating Surplus is given by:

$$\mathbf{GOS} = \widehat{\mathbf{Y}}^{\mathbf{D}}(\mathbf{p^f} - \hat{\mathbf{t}}^{\mathbf{Y}}\mathbf{p^b}) - \widehat{\mathbf{Y}}\,\mathbf{UC} + \mathbf{IM}[\mathbf{p^f} - (1 + \hat{\mathbf{t}}^{\mathbf{Y}})(\mathbf{p^W}e)] \tag{19}$$

This creates space for analysing how changes in the functional income distribution affect aggregate demand. For example, an increase in the wage share may boost consumption and reduce saving. An increase in profit share may raise investment but weaken short-run demand. These dynamics are particularly relevant in economies with dual economies (formal vs informal), marked by high income inequality, and precarious labour markets.

We can simulate the effect of income redistribution on growth, the consequences of transfer programmes (e.g., Bolsa Família), the demand-side impact of wage and price policies, and trade-offs between price stability and consumption dynamics. It also forms a crucial link with labour market dynamics, inflation and price formation, and government fiscal policy.

4.6. Labour Market and Productivity

Employment in each sector is determined by the volume of output and the labour productivity of that sector:

$$\mathbf{n} = (\hat{\mathbf{a}})^{-1}\mathbf{Y} \tag{20}$$

In which **n** is the employment sector vector.

If output increases (holding productivity constant), employment increases. If productivity increases (holding output constant), employment falls. Employment grows if output expands faster than productivity. Thus, this simple but powerful identity introduces a growth-employment-productivity trade-off, central to development and industrial policy. Wages are not static. Workers and firms adjust them over time based on labour market conditions, inflation expectations and productivity dynamics.

The model separates desired wages (what workers aim for) from actual wages (what they receive), introducing nominal rigidities and adjustment delays. Desired wages $\mathbf{w^d}$ are modelled as:

$$\dot{\mathbf{w}}^{\mathbf{d}} = \exp\left(\left[\,\gamma^N\left(\frac{\mathbf{Y'n}}{Pop} - \lambda^N\right)\right]\right) \cdot \left(\,\pi^y + \frac{\dot{a}_T}{a_T}\right)\mathbf{w^d} \qquad (21)$$

where γ^N is the employment sensitivity parameter, $\frac{\mathbf{Y'n}}{Pop}$ is the total employment rate, λ^N represents employment norm (natural rate), π^y is yearly expected inflation, $\frac{\dot{a}_T}{a_T}$ is aggregate productivity growth.

When employment is above the norm λ^N, workers demand higher wages. Desired wages also rise with inflation expectations and productivity gains (workers demand their fair share of growth). The exponential form ensures that wage pressure increases non-linearly with labour market tightness. This structure introduces a Phillips curve-like behaviour, where higher employment triggers wage growth, capturing real-world inflationary pressures in tight labour markets. Actual wages, $\mathbf{w}$, gradually converge toward desired wages. This reflects nominal rigidity due to contracts, bargaining delays, or institutional constraints (e.g. minimum wages).

$$\dot{\mathbf{w}} = \beta^w\,(\mathbf{w^d} - \mathbf{w}) \qquad (22)$$

where β^w is the wage adjustment speed. The lag between desired and actual creates room for inflationary inertia and labour market disequilibria, which is crucial in developing economies where informal employment, underemployment, and wage compression are prevalent.

Labour productivity follows an endogenous evolution. Productivity improves over time via capital accumulation and learning-by-doing. The evolution of sectoral productivity is given by:

$$\dot{\mathbf{a}} = \hat{\mathbf{a}}\,\left[\boldsymbol{\alpha}^{\mathbf{a}} \; + \gamma^a\left(\left(\widehat{\mathbf{Y^P}}\right)^{-1}\dot{\mathbf{Y}}^{\mathbf{P}} - \mathbf{g^w}\right)\right] \qquad (23)$$

where γ^a is the productivity sensitivity to investment rate in relation to world sectoral growth rate.

This means that productivity grows autonomously (baseline rate) but also responds to domestic investment dynamics. If a sector's capital stock expands faster than the global average, it learns and improves productivity. This reflects endogenous technological progress, especially through capital deepening and innovation diffusion.

The aggregate productivity level a_T, used in wage and macro variables, is computed as a weighted average:

$$a_T = \mathbf{a'Y}(\boldsymbol{\iota}'\mathbf{Y})^{-\mathbf{1}} \qquad (24)$$

and population evolves exogenously:

$$\dot{Pop} = Pop \cdot g^{Pop} \tag{25}$$

Labour market and productivity dynamics are closely linked to output through several key channels: employment is tied to output via an employment–output identity; consumption depends on wage income; wage–price interactions shape prices and inflation; and investment responds to capital–labour substitution. This framework enables the model to explore complex phenomena such as development traps, jobless growth, and the importance of inclusive structural transformation.

4.7. Price Formation and Inflation

Prices in ESTEEM are not market-clearing. Instead, firms use a cost-plus pricing strategy - an assumption in both Keynesian and structuralist economics. This approach is especially relevant in developing economies, where pricing is shaped by input costs, markups, and inventory conditions rather than marginal cost pricing or perfect competition.

The foundation of price formation is the unit cost (UC) of producing one unit of output in sector i. This includes: Direct labour costs (wages per unit of output), Intermediate input costs (based on the Leontief matrix), and environmental taxes (e.g. carbon or pollution levies).

$$\mathbf{UC} = (\hat{\mathbf{a}})^{-1}\mathbf{w} + \mathbf{A}'\mathbf{p^f} + \left(\mathbf{q^c} + \widehat{\boldsymbol{\phi}^{\mathbf{e}}}\mathbf{q^e}\right)t^c \tag{26}$$

Where $(\hat{\mathbf{a}})^{-1}\mathbf{w}$ is the wage cost per unit of output (unit labour cost), $\mathbf{A'p^f}$ is the cost of intermediate inputs (input–output matrix times prices), $\mathbf{q^c}$ is the CO_2 intensity (excluding energy), $\boldsymbol{\phi}^{\mathbf{e}}$ is the energy intensity, $\mathbf{q^e}$ is energy-related emissions, and t^c is the carbon tax rate. The first term reflects the productivity-adjusted wage cost. The second term reflects how much the sector depends on other sectors' outputs (technical coefficients). The third term reflects environmental costs, which rise with carbon intensity and taxation, introducing an explicit green policy lever. This provides a full accounting of production costs, which are used as a basis for price setting.

Firms determine their desired prices using a cost-plus pricing strategy. Starting with the unit cost **UC**, they apply a sector-specific mark-up to cover margins and ensure profitability. The resulting price reflects both production costs and market conditions influencing mark-up behaviour:

$$\mathbf{p^d} = (\mathbf{I} + \hat{\boldsymbol{\mu}})\mathbf{UC} \tag{27}$$

$\hat{\boldsymbol{\mu}}$ is the desired mark-up rate vector. This structure captures imperfect competition. Firms have some pricing power and can set prices above costs to secure profits. The mark-up reflects market conditions and strategic pricing behaviour.

The desired mark-up is modelled as an endogenous variable that adjusts in response to market conditions. Specifically, it rises with increasing demand pressure and falls when inventories accumulate, capturing firms' strategic pricing behaviour under varying degrees of market tightness.

$$\boldsymbol{\mu} = \widehat{\boldsymbol{\mu}_0} \exp\left[\widehat{\boldsymbol{\mu}_1}\left(\left(\widehat{\mathbf{V}}\right)^{-1}\widehat{\mathbf{V}^{\mathbf{d}}} - \mathbf{I}\right)\right]\left(2 + tanh(50\,(\mathbf{u}^{\mathbf{e}} - 1.125))\right) \quad (28)$$

In which $\boldsymbol{\mu}_0$ is the baseline mark-up. $\left(\widehat{\mathbf{V}}\right)^{-1}\widehat{\mathbf{V}^{\mathbf{d}}}$ is the inventory pressure ratio (desired over actual). $\mathbf{u}^{\mathbf{e}}$ is the capacity pressure ratio (expected demand over productive capacity). The actual basic price also depends on the structural characteristics of the sector. In the case of commodities, it evolves according to foreign price and exchange rate dynamics, as they are price-takers; for other goods and services, it adjusts towards the desired price:

$$\dot{\mathbf{p}}^{\mathbf{b}} = \widehat{\boldsymbol{\Omega}}\widehat{\mathbf{p}^{\mathbf{b}}}(\boldsymbol{\alpha}^{\mathbf{p}} + \dot{e}^N/e^N) + \left(\mathbf{I} - \widehat{\boldsymbol{\Omega}}\right)\beta^p(\mathbf{p}^{\mathbf{d}} - \mathbf{p}^{\mathbf{b}}) \quad (29)$$

When inventories are low (i.e. actual are below desired), firms can raise mark-ups. When expected demand is high relative to capacity, firms perceive strong market conditions and are confident to raise prices. When both pressures are weak, mark-ups fall - simulating price competition and margin erosion in downturns. This specification allows for price stickiness, cyclical profit margins, and non-linear inflation dynamics - key elements of real-world inflation behaviour.

The actual sales price faced by consumers and other sectors is influenced not only by desired price $\mathbf{p}^{\mathbf{d}}$, but also by the composition of domestic and imported goods in the total supply. The full formula is:

$$\mathbf{p}^{\mathbf{f}} = \left(\mathbf{I} + \widehat{\mathbf{t}^{\mathbf{Y}}}\right) \cdot \left[\left(\mathbf{I} - \widehat{\boldsymbol{\sigma}^{\mathbf{M}}}\right)\mathbf{p}^{\mathbf{b}} + \widehat{\boldsymbol{\sigma}^{\mathbf{M}}}\left(\mathbf{I} + \widehat{\mathbf{t}^{\mathbf{M}}}\right)\mathbf{p}^{\mathbf{w}}\, e^N\right] \quad (30)$$

This final price is given by sales taxes over the weighted average of basic domestic prices and world prices in domestic currency and import taxes This blended price reflects the real price paid by users, integrating global and domestic price pressures.

The consumer price index (CPI) (p^C) is a weighted average of sectoral final prices:

$$p^C = \mathbf{C}'\mathbf{p}^{\mathbf{f}}(\mathbf{C}'\boldsymbol{\iota})^{-1} \quad (31)$$

And inflation (π) is simply the growth rate of the CPI:

$$\pi = \dot{p}^C(p^C)^{-1} \quad (32)$$

This allows the model to track general price level evolution, which enters other blocks like: Wage setting, Interest rate setting, Real exchange rate dynamics.

To close the feedback loop, the model includes backward-looking inflation expectations:

$$\dot{\pi}^y = \pi - \pi^y \quad (33)$$

Where π^y is the yearly inflation (backward-looking expected inflation). This adaptive formulation reflects learning from past inflation, a common behaviour in both formal modelling and survey data. It plays a key role in shaping wage demands and monetary policy decisions.

4.8. Government and Fiscal Balance

The primary fiscal balance (government surplus SG) is defined as:

$$SG = T^H + T^Y + T^C + T^M - \mathbf{G}'\mathbf{p^f} + \mathbf{GOS}'\boldsymbol{\sigma}^\mathbf{G} - ST \tag{34}$$

Where T^H is income tax revenue; T^Y is Sales tax revenue; T^C is carbon tax revenue; T^M: import tax revenue; $\boldsymbol{\sigma}^\mathbf{G}$ is the share of profits distributed for the government. Revenues come from multiple sources: income, sales, import tariffs, environmental taxes, and profits. Expenditures include consumption of goods and services and income redistribution. This identity closes the fiscal accounts and feeds into the dynamic adjustment of government spending.

Public expenditure is endogenously adjusted based on the fiscal balance and GDP, via a simple fiscal rule:

$$\dot{\mathbf{G}} = g^x \cdot \mathbf{G} \cdot exp\left(\gamma^G \left(\frac{SG}{GDP} - \lambda^G\right) \cdot 100 \right) \tag{35}$$

where g^x is the autonomous growth rate of public spending, γ^G is the sensitivity to fiscal position, λ^G is the target surplus (or deficit), and GDP, the Nominal GDP.

If the fiscal position is better than the target (e.g. surplus above λ^G), government spending accelerates. If it is worse than tne target, spending is moderated to maintain sustainability. The exponential form ensures smooth adjustments and stabilising feedback. This approach introduces a countercyclical policy mechanism - the government can expand spending in downturns and consolidate in booms.

We then model several taxes. First, income tax (on wages and profits.):

$$T^H = \mathbf{t^{H}}' \cdot (\mathbf{GOS} + \widehat{\mathbf{w}}\,\mathbf{n}) \tag{36}$$

Sales tax (Collected on domestic and imported consumption):

$$T^Y = \left(\widehat{\mathbf{t^Y}}\mathbf{p^b}\right)'\mathbf{Y^D} + \left(\widehat{\mathbf{t^Y}}\left(\mathbf{I} + \widehat{\mathbf{t^M}}\right)\mathbf{p^w}e^N\right)'\mathbf{IM} \tag{37}$$

Import tax (Tariff revenue from imports):

$$T^M = \left(\widehat{\mathbf{t^M}}(\mathbf{p^w}e^N)\right)'\mathbf{IM} \tag{38}$$

Carbon tax (Applied to emissions (including energy use and process emissions)):

$$T^C = \mathbf{t^c}'\widehat{\mathbf{Y}}(\mathbf{q^c} + \widehat{\boldsymbol{\phi}^\mathbf{e}}\mathbf{q^e}) \tag{39}$$

These taxes serve both revenue and policy purposes—e.g. carbon taxes help internalise environmental costs.

Public transfers ST provide autonomous income support to households and are essential for equity and stability. Transfers evolve with:

$$\dot{ST} = (\alpha^N + \alpha^a + \pi^T) \cdot ST \tag{40}$$

Where α^N is population growth; α^a the autonomous productivity growth; π^T the inflation adjustment (target CPI growth). This ensures that transfers grow with the population, and reflect long-term productivity growth, also keeping pace with inflation. Transfers influence consumption behaviour, particularly for low-income households.

4.9. Monetary Policy and Exchange Rate

The central bank follows a Taylor rule. It sets its policy interest rate based on actual inflation and output deviations from target levels. The model uses a smooth approximation of a Taylor rule, avoiding abrupt changes:

$$i_T^P = \frac{1}{k}\log\left(1 + e^{k\left(\iota_0+\iota_1(\pi^m-\pi^T)+\iota_2\left(\frac{\iota\prime\mathbf{Y^e}}{\iota\prime\mathbf{Y^P}}-1\right)\right)}\right) \tag{41}$$

Where: i_T^P is the target nominal interest rate, π^m is expected inflation (backward-looking monthly inflation), π^T is the inflation target rate, $\frac{\iota\prime\mathbf{Y^e}}{\iota\prime\mathbf{Y^P}}$ is the aggregate output gap, ι_0 is the base rate, ι_1 is the Inflation sensitivity, ι_2 is the output sensitivity, k is the Smoothness parameter (larger = sharper response).

If inflation exceeds the target or the economy overheats, the interest rate rises. If inflation is low and utilisation is below capacity, monetary policy becomes accommodative. The logistic-log form ensures a smooth zero-bound policy rate. This allows the model to study monetary policy rules, rather than assuming fixed or exogenous rates.

The actual interest rate does not instantly match the target. It adjusts gradually, reflecting central bank inertia, political constraints, and credibility dynamics:

$$\dot{i^P} = \beta^i \, (i_T^P - i^P) \tag{42}$$

Where i^P is the actual nominal policy rate and β^i is the adjustment speed.

This delayed adjustment introduces time lags in monetary policy decision, capturing real-world sluggishness in interest rate changes. The interest rate faced by firms includes a risk premium over the base rate:

$$i^L = \mu^L + i^P \tag{43}$$

Where i^L is the lending rate for private investment decisions, μ^L is the risk or spread component (e.g. reflecting uncertainty, credit constraints). This rate directly influences investment decisions via the expected net profitability calculation, making it a core transmission mechanism of monetary policy.

The nominal exchange rate e^N (units of domestic currency per unit of foreign currency) adjusts endogenously in response to relative inflation (real exchange rate) and external imbalances (net exports):

$$\dot{e^N} = e^N \left[\gamma^p(\pi^T - \pi^W) + \gamma^x \left(\frac{NX}{GDP} - \lambda^x\right)\right] \quad (44)$$

Where π^T is the inflation target, π^W is external inflation (exogenous), NX is net exports, γ^p is the inflation feedback coefficient, γ^x is trade balance feedback, and λ^x, the external balance norm.

If domestic inflation exceeds foreign inflation, the currency depreciates. If the trade balance deteriorates, depreciation follows to restore competitiveness. Conversely, improvement in the current account leads to appreciation pressures. This equation captures the floating exchange rate adjustment mechanism without assuming full capital mobility or uncovered interest parity—more realistic for many developing countries.

The real exchange rate e^R is defined as:

$$e^R = e^N \cdot \frac{CPI^W}{p^C} \quad (45)$$

In which CPI^W is the foreign price index (exogenous), and p^C, domestic CPI (endogenous).

This measure reflects the relative price of foreign goods in real terms and influences: Import intensity, Export competitiveness, and inflation transmission (via import prices). A real depreciation improves competitiveness but may worsen inflation. A real appreciation lowers import prices but harms exports - key trade-offs in macroeconomic policy.

4.10. Environmental Dynamics

ESTEEM integrates environmental pressures directly into its macroeconomic core, allowing simulation of green transitions, environmental taxation, and ecological constraints. This block models how greenhouse gas emissions, land use, and blue water consumption evolve endogenously with output and structural change. Rather than treating the environment as an externality, it embeds it as a central feature of production dynamics and policy design, aligning with the sustainability transition literature and SDG-aligned economic modelling.

Sectoral emissions are driven by output levels and emission intensities, which are not fixed but change over time with technological upgrading and policy incentives. The model distinguishes: CO_2 emissions excluding land use ($CO2^{nL}$) and CO_2 emissions from land use, land-use change, and forestry (LULUCF) ($CO2^L$). Non-LULUCF Emissions are given by:

$$CO2^{nL} = \mathbf{Y^{P'}}\mathbf{q^c} + \mathbf{Y^{P'}}\widehat{\boldsymbol{\phi}^{\mathbf{e}}}\mathbf{q^e} \tag{46}$$

while land-use related emissions are driven by changes in capital accumulation in land-users sectors:

$$CO2^{L} = \dot{\mathbf{Y}}^{\mathbf{P}'}\widehat{\boldsymbol{\phi}^{\mathbf{L}}}\mathbf{q^L} \tag{47}$$

Where: $\mathbf{q^L}$ it the CO_2 per unit of land expansion and $\boldsymbol{\phi}^{\mathbf{L}}$ is land intensity. This term reflects that expanding productive capacity often involves land conversion, especially in agriculture or extractive sectors.

The model captures dynamic decoupling, where emissions per unit of output fall over time due to structural change (inter-sectoral) and technological change (infra-sectoral):

$$\dot{\boldsymbol{\sigma}}^{\mathbf{g}} = \left(\mathbf{I} - \widehat{\boldsymbol{\sigma}^{\mathbf{g}}}\right)\left[\phi^{g}\ \left(\left(\widehat{\mathbf{Y^P}}\right)^{-\mathbf{1}}\dot{\mathbf{Y}}^{\mathbf{P}} + \delta_j\right)\right] \emptyset \left(\left(\widehat{\mathbf{Y^P}}\right)^{-\mathbf{1}}\dot{\mathbf{Y}}^{\mathbf{P}} + 1\right) \tag{48}$$

Where: $\boldsymbol{\sigma}^{\mathbf{g}}$ is the current share of green technologies (0 to 1) and ϕ^g is the green technology adoption factor. As productive sectors grow and modernise, their green efficiency improves, reducing emission intensities. This dynamic translates into evolving pollution coefficients:

Energy-related emissions:

$$\mathbf{q^e} = \widehat{\mathbf{q}_0^{\mathbf{e}}}(1 - \boldsymbol{\sigma}^{\mathbf{g}} + \gamma^{e}\boldsymbol{\sigma}^{\mathbf{g}}) \tag{49}$$

Production-related emissions:

$$\mathbf{q^C} = \widehat{\mathbf{q}_0^{\mathbf{C}}}(1 - \boldsymbol{\sigma}^{\mathbf{g}} + \gamma^{c}\boldsymbol{\sigma}^{\mathbf{g}}) \tag{50}$$

Where γ^e and γ^c represent the relative emission-intensity of green technologies in relation to the new ones. As $\boldsymbol{\sigma}^{\mathbf{g}}$ increases, sectors become cleaner. In addition to emissions, dynamic ESTEEM tracks ecological pressures via land use and blue water consumption:

$$Q^{L} = \mathbf{Y}'\boldsymbol{\phi}^{\mathbf{L}} \tag{51}$$

$$Q^{W} = \mathbf{Y}'\boldsymbol{\phi}^{\mathbf{W}} \tag{52}$$

Where $\boldsymbol{\phi}^{\mathbf{L}}$ is the land use per unit of output, $\boldsymbol{\phi}^{\mathbf{W}}$ is the blue water consumption per unit of output. Both coefficients evolve similarly to emissions, improving with $\boldsymbol{\sigma}^{\mathbf{g}}$:

$$\boldsymbol{\phi}^{\mathbf{W}} = \boldsymbol{\phi}_0^{\mathbf{W}} \cdot (1 - \boldsymbol{\sigma}^{\mathbf{g}} + \gamma^{L}\boldsymbol{\sigma}^{\mathbf{g}}) \tag{53}$$

$$\boldsymbol{\phi}^{\mathbf{W}} = \boldsymbol{\phi}_0^{\mathbf{W}} \cdot (1 - \boldsymbol{\sigma}^{\mathbf{g}} + \gamma^{W}\boldsymbol{\sigma}^{\mathbf{g}}) \tag{54}$$

This enables the model to analyse eco-efficiency, sustainable intensification, and natural capital depletion.

5. Policy Simulations: Brazil's Ecological Transformation Plan (PTE)

Brazil's Ecological Transformation Plan (PTE), announced in 2023, aims to foster a green and inclusive structural transformation by stimulating investment, innovation, and reindustrialisation across key sectors. The plan reflects a developmental strategy that seeks to reconcile economic upgrading with environmental sustainability and social inclusion. This section integrates the policy architecture of the PTE into the ESTEEM, providing a framework for scenario analysis that captures short- and medium-term policy interventions within a consistent macroeconomic–environmental modelling structure.

The PTE comprises a combination of **cross-cutting** and **sector-specific** instruments, which can be categorised into short-term stimulus measures and long-term structural interventions. In the model, these policies are operationalised through adjustments in final demand, investment, input–output technical coefficients, import propensities, and sectoral productivity parameters. Table 1 summarises the main policy levers and their integration into ESTEEM's behavioural architecture.

5.1. Cross-Cutting Policies

In the short term, the PTE deploys fiscal tools (tax exemptions, subsidies) and financial instruments (green bonds, concessional credit) to reduce the cost of green investments. In ESTEEM, these are modelled as positive final demand shocks in capital goods sectors—particularly construction, electrical equipment, and green infrastructure. Credit policies, implemented via public development banks (e.g. BNDES, Finep), are reflected through increased investment due to lower interest rates and subsides in targeted sectors. Where local content requirements are binding, the model reduces import coefficients and shifts intermediate inputs toward domestic sourcing.

The PTE also introduces preferential procurement mechanisms to stimulate demand for domestic green technologies (e.g., electric buses, solar equipment). In the model, these are represented as increases in public consumption in relevant sectors, coupled with modifications to the technical coefficients matrix to reflect reduced reliance on imported components and greater upstream domestic linkages.

Medium- and long-term measures focus on expanding innovation ecosystems, university–industry collaboration, and technical training. These are implemented in the model as exogenous reductions in input coefficients (efficiency gains), productivity increases in selected sectors, and lower import propensities (import substitution). In the short term, rising public education expenditures are modelled as final demand increases in the education sector.

The PTE targets regional disparities by prioritising innovation-oriented sectors in underdeveloped areas (e.g., wind energy in the Northeast, biobased products in the Amazon and Cerrado). While ESTEEM is not spatially disaggregated, regional policies are captured through increased sectoral demand in activities with clear geographic concentration. The impact of such policies can be inferred through changes in output, employment, and trade in the targeted sectors.

5.2. Sectoral Policies

Short-term policies support renewable energy deployment through tax credits and investment subsidies, leading to demand increases in construction, electrical machinery, and component manufacturing. Domestic content rules are reflected by reducing import shares and increasing domestic input flows (e.g., metal-mechanical components). In the medium term, the PTE aims to build clean technology supply chains for solar panels, wind turbines, batteries, and hydrogen systems. ESTEEM models these shifts through adjustments in the IO matrix to reflect structural change and increased domestic sourcing. Where necessary, proxy sectors or aggregated categories are adapted to approximate these technological transitions.

Support for electric vehicles (EVs), public transport electrification, and charging infrastructure is modelled as final demand shocks in the automotive and equipment sectors. Import propensities are reduced to reflect local component production, particularly in battery technologies. The transition from diesel to electricity in transport modifies the energy input structure across modes. Long-term objectives to build a domestic EV industry are captured by gradually increasing domestic input shares and reducing dependence on imported vehicles and components. Mode shifts, such as rail expansion, are represented by adjusting demand shares across transport-related sectors.

Policies that promote value addition in agriculture—such as soybean processing, second-generation cellulose, and cooperative support—are simulated through increased demand for food manufacturing and agroindustrial sectors. Export substitution of raw commodities is modelled by reallocating agricultural output toward domestic industrial use. In the long term, the PTE supports high-tech bioeconomy sectors (e.g., pharmaceuticals, cosmetics), which are represented by expanding existing sectors or introducing proxy categories with biodiversity-based inputs. These measures imply a structural reallocation of inputs and a transition toward higher value-added and lower environmental-intensity production.

Industrial upgrading is supported by incentives for efficient machinery, recycling systems, and cleaner technologies. These interventions raise investment in capital goods and reduce input–output technical coefficients for raw materials and fossil-based energy. The circular economy is modelled through modified IO coefficients that incorporate inter-sectoral symbiosis (e.g., waste as an input for other industries), expanding domestic linkages and reducing import leakages. Medium-term transformations—such as green steel, biodegradable plastics, and smart electronics—are approximated through shifts in input structures and the addition of recycling and remanufacturing loops.

5.3. Policy Modelling in ESTEEM

In operational terms, ESTEEM integrates these policy levers via endogenous and exogenous mechanisms. Short-term measures operate primarily through endogenous behavioural responses—stimulating demand, investment, and price adjustments. Long-term structural changes are introduced exogenously through shifts in coefficients, productivity parameters, and sectoral definitions, consistent with planned policy trajectories and empirical data when available.

This dual treatment allows the model to simulate transition dynamics under different assumptions about policy efficacy, implementation lags, and sectoral absorption capacity. For instance, scenarios can be constructed to compare the outcomes of: (1) fiscal stimulus without structural reforms; (2) coordinated green industrial policy with credit and innovation support; or (3) import-substituting reindustrialisation combined with circular economy expansion. These simulations provide insights into output growth, trade balance, employment creation, and emissions trajectories under alternative PTE strategies.

6. Conclusion

This paper has introduced ESTEEM, a continuous-time, structuralist system dynamics model tailored to the realities of open developing economies. By extending the Leontief input–output framework to incorporate behavioural dynamics, environmental feedbacks, and macrofinancial constraints, the model offers a robust platform for simulating green transitions under disequilibrium conditions. Key innovations include the endogenisation of investment, price formation, trade dynamics, and ecological pressures—each critical to understanding how structural transformation unfolds in constrained policy environments.

The model's relevance is demonstrated through its application to Brazil’s Ecological Transformation Plan (PTE), a national strategy combining industrial policy with sustainability objectives. The integration of PTE policy instruments—ranging from fiscal stimuli and credit lines to clean technology promotion and circular economy interventions—highlights how ESTEEM can operationalise diverse policy levers within a coherent macroeconomic–ecological framework. By modelling the dual structure of short-term demand effects and long-term structural shifts, the framework enables scenario analyses that reflect real-world implementation paths and sectoral interdependencies.

This approach addresses critical limitations of both static input–output models and neoclassical general equilibrium frameworks, offering instead a dynamic, demand-led alternative that accommodates technological change, capacity constraints, and behavioural adaptation. It captures transition frictions—such as greenflation, employment reallocation, and external vulnerability—while allowing for the exploration of policy complementarities, such as public procurement combined with R&D support or domestic content rules in emerging green sectors.

While the current version provides a rich foundation for policy evaluation, further model development is planned. This includes the integration of household heterogeneity, financial sector channels, regional disaggregation, and endogenous innovation dynamics. Empirical calibration using Brazilian sectoral and environmental data will also support the construction of stylised policy scenarios aligned with the PTE's implementation timeline.

Ultimately, ESTEEM contributes to the broader literature on ecological macroeconomics and green structural transformation. It provides policymakers with a flexible and transparent tool to assess the risks, trade-offs, and opportunities embedded in transition strategies—supporting more informed and coherent decision-making in the context of climate urgency and developmental asymmetries.

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