Societal Evolution Computational Model (SECM) V0.5 ALPHA

Technical White Paper

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Abstract

The Societal Evolution Computational Model (SECM) V0.5 ALPHA is an original modular computational framework designed to analyze the evolution of social stress, carrying capacity, and systemic resilience over time. Although the model draws on established energy equivalence concepts for its KW Productivity Equivalent (KWPE) metric, all other components—including the mathematical structure, integration logic, and module interactions—are original contributions by the author.

The model is not a predictive "crystal ball," but rather an exploratory tool to identify generalized patterns in the coevolution of societal productivity, complexity, and stability. SECM is inherently time-agnostic: its stepwise calculations are driven exclusively by changes in productive capacity (X), and the temporal resolution of the results is determined solely by the interval of the input data (e.g., annual, decadal). This feature allows the model to operate on diverse historical and contemporary datasets, provided that the intervals remain consistent.

By incorporating representative and accessible variables, SECM enables reproducibility while allowing users to substitute better proxies when available. Historical data gaps and prestatistical proxies must be supplied by the user, as the author does not provide archaeological or historical dataset recommendations. The present paper focuses on the computational workflow and mathematical formulation; methodology and validation details are provided in separate documents.

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1 Introduction

The Societal Evolution Computational Model (SECM) V0.5 ALPHA is an original modular computational framework designed to explore the generalized dynamics of societal stress, carrying capacity, and systemic resilience. Although many prior models address economic growth, environmental limits, or social change individually, SECM integrates these domains into a unified structure that is data-driven and adaptable across contexts.

The core purpose of the model is **exploration**, not predictive. SECM is intended to serve as an analytical framework for investigating how productive capacity, social complexity, and systemic vulnerability interact over extended periods. The model is suitable for historical analysis, counterfactual scenarios, and forward-looking stress testing —-provided the user understands that the outputs represent structured computations of relationships between variables, not deterministic forecasts of future events.

The SECM architecture is made up of distinct computational modules linked through well-defined data flows. These include modules to calculate productive capacity (X), innovation dividends, social complexity, systemic vulnerability (Ω), net tension drivers (Z_{eff}), societal stress index (Y), carrying capacity (Y_{limit}), and overload dynamics (Crisis Pool S_t and Resilience Reset I_{reset}).

An important structural feature of SECM V0.5 ALPHA is its **time-agnostic nature**. The model does not contain an inherent time variable. Instead, it operates in discrete steps driven exclusively by changes in productive capacity (X), and the temporal resolution of the simulation is entirely determined by the interval of the input data. For example, annual data produce annual steps, while decadal data produces decadal steps. This design allows the model to be applied to both modern statistical series and reconstructed historical data sets of varying temporal granularity.

In the present paper, the focus is on computational design and mathematical formulation. Data collection methodology, parameter estimation procedures, and validation results are documented separately in dedicated methodology and verification manuscripts.

2 Model Philosophy and Variable Design Principles

2.1 Philosophical Basis

SECM V0.5 ALPHA is based on the premise that the evolution of human societies can be analyzed through quantifiable interactions between productive capacity, social complexity, systemic vulnerability, and carrying capacity. Unlike traditional forecasting models, SECM does not attempt to predict specific events or dates. Instead, it serves as a **conceptual and computational laboratory** for testing how changes in one domain may propagate to others under varying structural conditions.

This philosophical orientation ensures that SECM remains relevant in different temporal and geographic contexts. By abstracting away from rigid time dependencies, the model captures the structural logic of societal evolution rather than binding itself to historical timelines.

2.2 Non-Predictive Nature and Scope Limitations

The model is **not a "crystal ball"** for foretelling the future. Its outputs are best interpreted as structured indicators of stress and capacity dynamics, depending on the input variables and parameters chosen. The framework can highlight potential tipping points or capacity thresholds, but the actual timing, form, and consequences of such transitions are beyond its predictive remit.

Furthermore, the model does not address normative judgments about societal stability, desirability of certain outcomes, or prescriptive interventions. Such analyses must be conducted separately, integrating SECM outputs with qualitative assessments and domain-specific expertise.

2.3 Variable Selection Rationale

Input variables in SECM are chosen for three main reasons:

1. **Representativeness**: Each variable corresponds to a structural component of societal functioning (e.g., economic productivity, demographic pressure, institutional trust).

2. **Accessibility**: The variables are drawn from widely available datasets, such as the World Bank, OECD, and World Values Survey.

3. **Substitutability**: The model allows users to replace the default variables with alternative proxies that are better suited to their specific research contexts.

Historical or anticipatistic periods may require the use of proxy indicators (e.g., archaeological yield estimates for agricultural productivity). The identification, validation, and integration of such proxies are the responsibility of the user. The author does not provide archaeological or historical data sets, as this is outside of the intended scope of the model and the author's expertise.

2.4 Development Status

SECM V0.5 ALPHA remains under active development and iteration. Although the current structure and formulae have undergone extensive internal testing and validation against multiple historical cases, the model is expected to evolve as additional data sources, theoretical insights, and computational techniques become available.

3 Computational Architecture

3.1 Overview

The SECM V0.5 ALPHA framework is organized as a sequence of interconnected computational modules, each responsible for transforming specific categories of input data into intermediate or final indicators. This modular design improves transparency, facilitates troubleshooting, and allows the targeted substitution or refinement of individual components without altering the entire system.

The architecture is divided into the following:

- **Input Mapping Modules** – Standardizes and normalizes raw data to model compatible formats.
- **Core Computational Modules** - Processes normalize inputs into key intermediate indicators (X, X_{bonus}, Z_c, Ω, Z_{eff}).
- **Output Modules** – Calculates final societal stress and capacity metrics (Y, Y_{limit}, S_t, I_{reset}) and produces results for analysis.

3.2 Logical Structure

Figure 1 presents the logical structure of SECM V0.5 ALPHA in compact form. Each module is represented as a functional block, with arrows denoting the direction of the data flow.

3.3 Key Modules

1. **Productive Capacity Module (X)** – Computes actual and normalized productivity from energy and labor-equivalent metrics.
2. **Innovation Dividend Module (X_{bonus})** – Captures gains from STEM workforce share, education rate, TFP growth, and patent density.
3. **Social Complexity Module (Z_c)** – Aggregates inequality, social trust, demographic stress, and governance indicators.
4. **System Vulnerability Module (Ω)** – Integrates financial and structural risk indicators into a composite vulnerability measure.
5. **Net Tension Driver Module (Z_{eff})** – Combines social complexity, innovation, and exogenous shocks into an effective social tension factor.
6. **Societal Stress Index Module (Y)** – Calculates total societal stress as a function of productive capacity, net tension, and other modifiers.

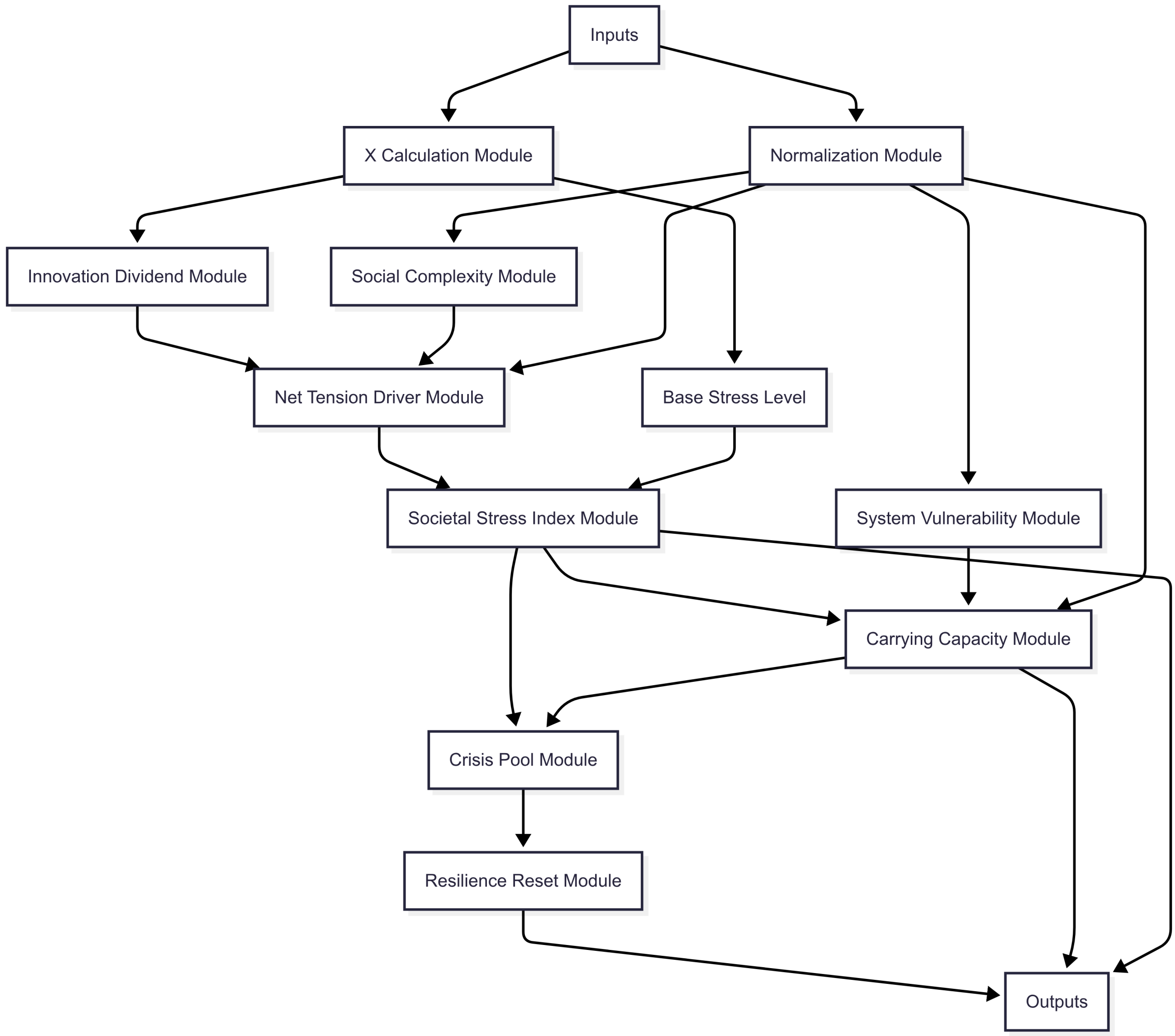

Figure 1: Logical Structure of SECM V0.5 ALPHA (Compact Representation)

7. **Carrying Capacity Module** (Y_{limit}) – Estimates maximum sustainable stress before systemic instability is likely.

8. **Crisis Pool Module** (S_t) – Tracks cumulative societal overload beyond capacity.

9. **Resilience Reset Module** (I_{reset}) – Represents periodic reductions in overload due to societal adaptation or restructuring.

3.4 Execution Flow Diagram

The execution flow is presented in Figure 2, showing the order in which data move through the system during a single simulation run.

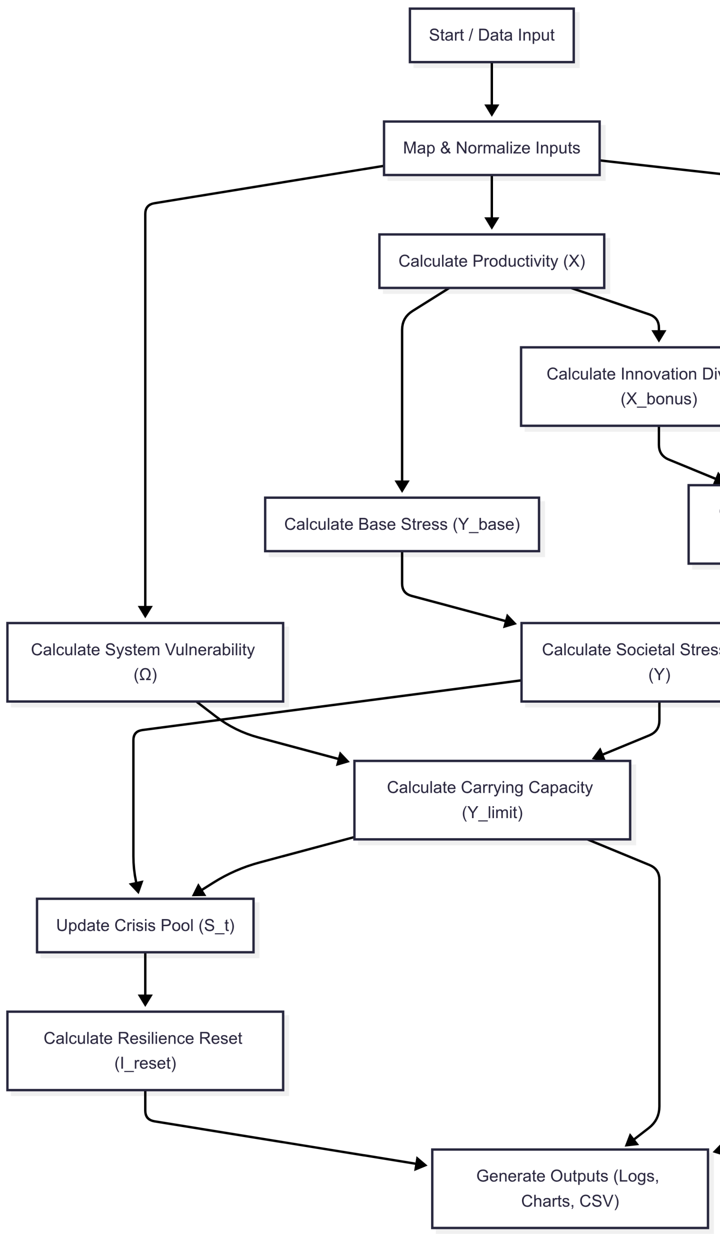

Figure 2: Execution Flow of SECM V0.5 ALPHA (Compact Representation)

4 Execution Flow

4.1 Time-Agnostic Operation

It is important to note that SECM V0.5 ALPHA does not contain any inherent time variable. All calculations proceed in discrete steps driven by changes in productive capacity (X), not by calendar time. The temporal resolution of results is entirely determined by the time interval of the input data used. For example, if inputs are annual, each model step represents one year; if inputs are decadal, each step represents ten years. This design ensures that the model can operate across datasets of varying temporal granularity, provided that the intervals remain consistent throughout a simulation.

The ordering of modules in the computational sequence reflects logical dependencies, not chronological causality. This means that while the flow of computation is fixed, it should not be interpreted as representing the actual timing of societal processes.

4.2 Stepwise Process Overview

A single execution cycle of SECM V0.5 ALPHA follows the general structure below:

1. **Input Mapping and Normalization** – Raw data is standardized and scaled to ensure comparability.

2. **Core Capacity Calculation (X)** – Productive capacity is calculated from energy, labor and other base metrics.

3. **Innovation Dividend Calculation ($X_{\mathbf{bonus}}$)** – Technological and institutional gains are incorporated.

4. **Social Complexity (Z_c) and System Vulnerability (Ω)** – Societal structural stresses and systemic risks are quantified.

5. **Net Tension Driver (Z_{eff})** – Integrates complexity, innovation, and shocks into a net pressure indicator.

6. **Societal Stress (Y) and Carrying Capacity (Y_{limit})** - The final measures of stress and capacity are calculated.

7. **Crisis Pool (S_t) and Resilience Reset (I_{reset})** – Tracks overload accumulation and periodic relief.

8. **Output Generation** – Results are logged, visualized, and optionally exported.

4.3 Parallel and Sequential Dependencies

Although most modules are executed in a linear sequence, some are computed in parallel to improve efficiency:

- Z_c and Ω are derived from different subsets of normalized inputs and can be calculated independently before contributing to Y_{limit} and Z_{eff}.
- S_t and I_{reset} depend on prior Y and Y_{limit} outputs but do not feed back into the same cycle.

5 Formal Specification of Model Equations

This section provides the complete mathematical specification of the Societal Evolution Computational Model (SECM) V0.5 ALPHA. All variables, parameters, and derived quantities are introduced systematically, with explicit equations and explanatory notes. The aim is to eliminate ambiguity by ensuring that every formula used in the implementation has a transparent theoretical definition and a clear correspondence to its coded version.

The model is stepwise and time-agnostic: it does not evolve continuously in physical time but rather through discrete computational steps. The apparent "time scale" of the simulation is thus entirely determined by the resolution of the input data set. For example, if annual data are used, each iteration corresponds to one year; if decadal data are used, each iteration corresponds to one decade.

5.1 Core Productivity (X)

Productive capacity is the main foundation of SECM, indicated by X. It is defined as the sum of three components: (i) total primary energy supply, (ii) animal power converted to equivalent units of energy, and (iii) human labor force converted to equivalents in kilowatt hours using the KWPE (*Kilowatt Productivity Equivalent*) method.

$$X_{\text{real},t} = PE_t + AP_t + \frac{130 \cdot Pop_t}{10^6} \tag{1}$$

where:

- PE_t = total primary energy at step t (in millions of kWh).
- AP_t = animal power converted to energy (in million kWh).
- Pop_t = total population at step t.
- The constant 130 reflects the assumed annual equivalent productivity per capita (kWh per person per year), consistent with historical labor productivity conversion.

The model normalizes this value to a baseline established in the first step.

$$X_{\text{norm},t} = \frac{X_{\text{real},t}}{X_{\text{base}}} \tag{2}$$

where X_{base} is the reference capacity fixed in the first valid iteration. If the denominator is zero or negative, it is set to one to avoid division instability.

Normalization ensures that subsequent ratios and derived indicators remain dimensionless and comparable across nations and eras.

5.2 Innovation Dividend (X_{bonus})

In addition to baseline productive capacity, SECM incorporates an *innovation dividend* that captures incremental productivity gains from technological progress, education, and institutional quality. This term is multiplicative rather than additive, ensuring that productivity gains only manifest when several enabling factors co-occur.

$$X_{\text{bonus},t} = \theta \cdot STEM_t \cdot EduRate_t \cdot (1 + TFP_t) \cdot \left(\frac{PatentDensity_t}{PatentDensity_{t-1}}\right) \cdot \left(\frac{X_{\text{real},t}}{X_{\text{real},t-1}}\right)^P \tag{3}$$

with a normalized and clipped form:

$$X_{\text{bonus,norm},t} = \text{clip}\big(X_{\text{bonus},t},\ 0,\ 5\big). \tag{4}$$

where:

- θ = scaling factor for innovation returns.
- $STEM_t$ = proportion of STEM-skilled labor in the workforce at step t.
- $EduRate_t$ = education enrollment or attainment rate.
- TFP_t = total factor productivity index.
- $PatentDensity_t = \frac{PatentCount_t}{Pop_t} \cdot 10^6$ = patents per million inhabitants.
- P = elasticity exponent linking real capacity growth to innovation effectiveness.

Interpretation. The dividend increases when a country simultaneously increases STEM share, education coverage, and TFP, while sustaining patent output and real capacity growth. If any factor stagnates, the product attenuates the effect. The upper clip at 5 prevents unstable divergence in cases of extreme statistical values.

—

5.3 Social Complexity (Z_c)

Social complexity aggregates multiple structural and behavioral indicators that contribute to societal stress. Unlike X, which represents productive capacity, Z_c encodes distributional, institutional, and demographic pressures.

$$
\begin{aligned}
S_{\text{murder},t} &= \text{scale}_{[0,1]}(MurderRate_t) \cdot \sqrt{2}, && (5)\\
S_{\text{poverty},t} &= \text{scale}_{[0,1]}(PovertyRate_t) \cdot \sqrt{2}, && (6)\\
MCapGDP_t^* &= \min(MCapGDP_t,\, 3), \quad MCapGDP_t^{\text{norm}} = \frac{MCapGDP_t^*}{3}, && (7)\\
PeoplePerHa_t &= \frac{Pop_t}{ArableLand_t}, && (8)\\
Spopdens_t &= \text{scale}_{[0,1]}\Big(UrbanRate_t \cdot \ln(1 + PeoplePerHa_t)\Big), && (9)\\
Z_{c,t} &= \text{clip}\Big(\text{mean}(Gini_t, S_{\text{murder},t}, S_{\text{poverty},t}, MCapGDP_t^{\text{norm}}, 1 - Trust_t, Spopdens_t),\ 0,\ 5\Big). && (10)
\end{aligned}
$$

where:

- $Gini_t$ = income inequality index.
- $MurderRate_t$, $PovertyRate_t$ = agents of societal violence and deprivation.
- $MCapGDP_t$ = market capitalization as a share of GDP, capped at 3 to avoid dominance by financialized economies.
- $Trust_t$ = survey-based social trust index; $1 - Trust_t$ represents distrust.
- $UrbanRate_t$ = proportion of the population living in urban areas.
- $PeoplePerHa_t$ = population density per hectare of arable land.
- $Spopdens_t$ = compound indicator of logarithmically adjusted urbanization pressure.

Interpretation. Z_c functions as an averaged bounded measure of systemic complexity and latent stress. Violent crime and poverty are given $\sqrt{2}$ weight to reflect their disproportionate role in destabilization. Capping and clipping ensure robustness across national contexts, preventing extreme values from skewing comparisons.

5.4 System Fragility (Ω)

System fragility quantifies the vulnerability of a society to a crisis, defined as a weighted combination of savings, unemployment, debt, and logistic performance. The formula implemented in SECM V0.5 ALPHA is as follows:

$$\Omega_t \;=\; \mathrm{clip}\Big(-Savings_t + \sqrt{2}\cdot Unemployment_t + DebtRatio_t - \tfrac{LPI_t}{10} + \mathrm{OmegaShock}_t,\; -5,\; 5\Big) \tag{11}$$

where:

- $Savings_t$ = normalized household or national savings index (higher savings reduce fragility).
- $Unemployment_t$ = unemployment rate, normalized to $[0, 1]$; it is entered with a weight of $\sqrt{2}$ to reflect its nonlinear destabilizing impact.
- $DebtRatio_t$ = debt-to-GDP ratio, linearly increasing fragility.
- LPI_t = Logistics Performance Index (World Bank scale $[1, 5]$); divided by 10 to normalize its effect, higher values reduce fragility.
- $\Omega\mathrm{Shock}_t$ = exogenous vulnerability shock (positive for disasters or crises, negative for improvements such as foreign aid).

The clip operator truncates the values to the interval $[-5, 5]$:

$$\mathrm{clip}(x, -5, 5) = \begin{cases} -5 & \text{if } x < -5, \\ x & \text{if } -5 \le x \le 5, \\ 5 & \text{if } x > 5. \end{cases}$$

Interpretation.

- High savings ($Savings_t$) stabilize society and pull Ω down.
- The rise in unemployment ($Unemployment_t$) has amplified the destabilizing effect due to the $\sqrt{2}$ factor.
- Larger debt burdens directly increase fragility.
- Stronger logistics performance (LPI_t) mitigates fragility.
- $\Omega_{\mathrm{Shock}t}$ introduces sudden changes (e.g., natural disasters, pandemics, reforms, or aid).

The clipping ensures that Ω remains bounded, avoiding runaway growth or collapse in simulation. This makes the fragility channel robust to outliers in the input data.

—

5.5 Effective Tension (Z_{eff})

Whereas Z_c is descriptive, Z_{eff} is a transformed version that acts as the direct driver of societal stress dynamics. It amplifies small changes near stability thresholds and preserves sign information.

$$Z_{\text{eff},t} = \begin{cases} (1 + Z_{c,t})^2 - 1, & \text{if } Z_{c,t} \geq 0, \\ -\big[(1 + Z_{c,t})^2 - 1\big], & \text{if } Z_{c,t} < 0. \end{cases} \tag{12}$$

including exogenous shocks:

$$Z_{\text{total},t} = Z_{\text{eff},t} + ZShock_t \tag{13}$$

where:

- $Z_{c,t}$ = normalized social complexity (from Eq. 13).
- $ZShock_t$ = exogenous shock term applied to the tension channel.
- Transformation $(1 + Z_c)^2 - 1$ ensures convex amplification of deviations, while preserving the possibility of negative values when shocks reduce tension.

Interpretation. Z_{eff} is a sensitivity amplifier. When Z_c is small, the changes are modest; when Z_c grows, the quadratic form accelerates the growth of stress. The sign-preserving design allows for both constructive (stress-increasing) and beneficial (stress-relieving) shocks. Thus, Z_{total} becomes the actual variable entering the dynamics of Y in the next section.

5.6 System Vulnerability (Ω)

The vulnerability of the system measures how susceptible the system is to stress transmission given macro–institutional conditions. In SECM, it is a bounded linear composite of savings, unemployment, debt, and logistics performance, plus an exogenous shock:

$$\Omega_t^* = -\,\text{SavingsRate}_t \;+\; \sqrt{2} \cdot \text{UnemploymentRate}_t \;+\; \text{DebtRate}_t \;-\; \frac{\text{LPI}_t}{10}, \tag{14}$$

$$\Omega_t = \text{clip}\big(\,\Omega_t^* + \Omega\text{Shock}_t,\; -5,\; 5\,\big). \tag{15}$$

Variables and roles.

- $\text{SavingsRate}_t \in [0, 1]$: higher savings reduce vulnerability (negative sign).
- $\text{UnemploymentRate}_t \in [0, 1]$: increases vulnerability; weighted by $\sqrt{2}$ to reflect its large destabilizing power.

- $\text{DebtRate}_t \in [0, 1]$: debt burden raises vulnerability.
- $\text{LPI}_t \in [0, 10]$: Logistics Performance Index; better logistics lower vulnerability via $-\text{LPI}/10$.
- ΩShock_t: exogenous shock to vulnerability; < 0 denotes resilience gains, > 0 denotes adverse shocks.

Interpretation. Ω is bounded in $[-5, 5]$ to prevent non-physical divergence and to match the implementation safeguards. It does not directly change productivity; instead, it conditions the carrying capacity Y_{limit} (Section 5.10).

5.7 Net Tension Driver (Z_{eff})

SECM converts structural complexity and policy cushions into a single net tension driver that drives stress dynamics. The construction proceeds in four steps: mixture → theoretical clipping → linear rescaling → sign-preserving quadratic amplification.

(i) Linear mixture.

$$\tilde{Z}_t = Z\text{Shock}_t - \text{relax}_t + \gamma_S Z_{c,t} - \gamma_X X_{\text{bonus,norm},t} + \text{Drift}_t. \tag{16}$$

Components.

- $Z\text{Shock}_t$: exogenous shock to tension; < 0 relieves tension, > 0 intensifies it.
- $\text{relax}_t \in [0, 1]$: aggregate social cushion. In implementation, relax_t is the *mean of available coverage rates* amongHealthcareCov, PensionCov, FreeEduCov, UnempInsCov}; if these are not available, it goes back to a composite SocSecIndex_t.
- $\gamma_S > 0$: weight on structural complexity $Z_{c,t}$.
- $\gamma_X > 0$: weight on innovation dividend $X_{\text{bonus,norm},t}$ as *tension counter-term.*
- Drift_t: optional small drift control of low-frequency bias (often set to 0 in validation).

(ii) Theoretical clipping.

$$\tilde{Z}_t^{\text{clip}} = \text{clip}\big(\tilde{Z}_t, -Z_{\max}, Z_{\max}\big), \qquad Z_{\max} = 7. \tag{17}$$

(iii) Linear rescaling to a compact interval.

$$Z_t^{\text{scaled}} = \frac{Z_{\text{scale}}}{Z_{\max}} \tilde{Z}_t^{\text{clip}}, \qquad Z_{\text{scale}} = 1.4. \tag{18}$$

(iv) Sign-preserving quadratic amplification.

$$Z_{\mathrm{eff},t} \;=\; \operatorname{sign}\!\big(Z_t^{\mathrm{scaled}}\big)\;\Big((1+|Z_t^{\mathrm{scaled}}|)^2-1\Big). \tag{19}$$

Interpretation. Small tensions remain small after steps (ii)–(iii); step (iv) then increases sensitivity near critical zones while preserving the sign, so that beneficial policies or good shocks (negative side) reduce stress symmetrically.

5.8 Societal Stress (Y)

Societal stress Y evolves from a baseline that reflects current capacity and distribution, plus an increase proportional to the change in capacity modulated by net tension and population pressure.

Baseline.

$$Y_{\mathrm{base},t} \;=\; a_0 \;+\; a_1\,X_{\mathrm{norm},t} \;+\; b_1\,\mathrm{Gini}_t \;+\; \mu\,\ln\!\big(1+X_{\mathrm{real},t}\big). \tag{20}$$

Sensitivity pack. Let $\Delta X_t = X_{\mathrm{norm},t} - X_{\mathrm{norm},t-1}$. Define

$$\kappa_t \;=\; k_Y\cdot\Big(1+Z\mathrm{ImpactK}\cdot Z_{\mathrm{eff},t}\Big)\cdot\Big(1+\mathrm{PopPressure}_t\Big). \tag{21}$$

Three-regime update.

$$Y_t \;=\; \begin{cases} Y_{\mathrm{first}}, & \text{first observed step,}\\[4pt] Y_{\mathrm{base},t}+\Delta X_t\,\kappa_t, & \text{second step,}\\[4pt] Y_{t-1}+\Delta X_t\,\kappa_t, & \text{subsequent steps.}\end{cases} \tag{22}$$

Roles and notes.

- a_0, a_1, b_1, μ: baseline coefficients; $a_1 > 0$ links the stress level to the productive scale, $b_1 > 0$ accounts for distributional strain.
- $k_Y > 0$: base gain from capacity change to stress change.
- ZImpactK: how strongly Z_{eff} modulates the gain.
- $\mathrm{PopPressure}_t$: land–people constraint (defined in Section 5.9); multiplicative, so low-energy dense societies amplify ΔX-induced stress.
- Y_{first}: initial stress anchor (provided by the user or inferred), used once to position the curve vertically without altering its trend shape.

5.9 Population Pressure (PopPressure)

Population pressure reflects how population–land constraints amplify the translation of capacity changes into stress. It compares people-per-arable hectare with per-capita energy-equivalent capacity.

$$
\begin{aligned}
\mathrm{PeoplePerHa}_t &= \frac{\mathrm{Pop}_t}{\mathrm{ArableLand}_t}, && (23)\\
\mathrm{KWPE}_t^{\mathrm{human}} &= \frac{130 \cdot \mathrm{Pop}_t}{10^6} \quad \text{(million kWh)}, && (24)\\
\mathrm{KWPE}_{pc,t} &= \frac{\left(\mathrm{PE}_t + \mathrm{AP}_t + \mathrm{KWPE}_t^{\mathrm{human}}\right) \times 10^6}{\mathrm{Pop}_t} \quad \text{(kWh per person-year)}, && (25)\\
\mathrm{PopPressure}_t &= \begin{cases} \dfrac{L \cdot \mathrm{PeoplePerHa}_t}{\mathrm{KWPE}_{pc,t}}, & \text{if } L > 0 \text{ and } \mathrm{KWPE}_{pc,t} > 0, \\ 0, & \text{otherwise,} \end{cases} && (26)
\end{aligned}
$$

with L the land capacity coefficient (default $L = 15$ kWh/(person·yr)).
Interpretation. Higher people-per-arable density raises pressure; higher per-capita energy capacity alleviates it. The term is unit safe and bounded by construction in implementation via the guard conditions.

5.10 Carrying Capacity (Y_{limit})

The carrying capacity is the instantaneous ceiling against which stress is compared. It responds to military burden, vulnerability, and recent negative capacity changes.

Base capacity net of military burden.

$$
\mathrm{baseX}_t = X_{\mathrm{norm},t} \cdot \left(1 - \mathrm{MilitaryRatio}_t\right). \tag{27}
$$

Piecewise vulnerability response.

$$
\hat{Y}_{\mathrm{limit},t} = \begin{cases} \mathrm{baseX}_t \cdot k_{\mathrm{limit}} \cdot \left(1 + |\Omega_t|\right), & \Omega_t \le 1, \\ \mathrm{baseX}_t \cdot \dfrac{k_{\mathrm{limit}}}{1 + \Omega_t}, & \Omega_t > 1. \end{cases} \tag{28}
$$

Decay under negative capacity change. If $\Delta X_t < 0$ and $\beta > 0$,

$$
\hat{Y}_{\mathrm{limit},t} \leftarrow \frac{\hat{Y}_{\mathrm{limit},t}}{(1+\beta)\,(1 + |\Delta X_t|)}. \tag{29}
$$

Perturbation and floor.

$$Y_{\text{limit},t} \;=\; \max\bigl(0,\; \hat{Y}_{\text{limit},t} + \varepsilon\bigr). \tag{30}$$

Roles and notes.

- MilitaryRatio_t *reduces* usable capacity via $(1 - \text{MilitaryRatio}_t)$.
- $k_{\text{limit}} > 0$: scale from base capacity to carrying ceiling.
- $\beta \geq 0$: intensifies carrying reduction after negative capacity shocks.
- ε: small perturbation that prevents degenerate ties in edge cases.

5.11 Crisis Pool (S_t)

The crisis pool accumulates stress overshoot and decays when stress is within the ceiling.

$$S_t \;=\; \begin{cases} S_{t-1} + \bigl(Y_t - Y_{\text{limit},t}\bigr), & \text{if } Y_t > Y_{\text{limit},t}, \\ S_{t-1} \cdot (1 - \lambda_S), & \text{if } Y_t \leq Y_{\text{limit},t}, \end{cases} \tag{31}$$

with $0 < \lambda_S < 1$ the decay rate.
Interpretation. S_t summarizes the cumulative overshoot; it is a slow variable that can condition policy triggers or resets.

5.12 Resilience Reset (I_{reset})

A simple threshold rule can be used to flag system-wide reset events:

$$I_{\text{reset},t} \;=\; \mathbb{I}\{\, S_t \;\geq\; Y_{\text{limit},t} \,\}\,, \tag{32}$$

where $\mathbb{I}\{\cdot\}$ is the indicator function. The specific downstream use of I_{reset} (e.g., parameter reinitialization or regime switching) is modeler- or application-dependent.

6 Variable Definitions and Descriptions

This chapter defines all state variables, indicators, parameters, and exogenous controls appearing in Section 5. Units and bounds are reported whenever applicable; default values refer to the reference implementation used in the validation experiments.

6.1 Core State Variables

Symbol	**Definition / Role**	**Unit / Range**

$X_{\text{real},t}$	Real productive capacity: total primary energy + animal power + human KWPE (Eq. 1). Drives all downstream ratios and deltas.	million kWh, ≥ 0
X_{base}	Normalization baseline: first positive X_{real} in a run (or user-provided fallback). Ensures cross-period comparability.	million kWh, > 0
$X_{\text{norm},t}$	Normalized capacity $X_{\text{real},t}/X_{\text{base}}$ (Eq. 2). Scale-free driver used throughout.	dimensionless
ΔX_t	Capacity change $X_{\text{norm},t} - X_{\text{norm},t-1}$; the only increment that propagates into Y updates (Eq. 5.8).	dimensionless
$Y_{\text{base},t}$	Baseline stress from scale and distribution: $a_0 + a_1 X_{\text{norm},t} + b_1 \text{Gini}_t + \mu \ln(1 + X_{\text{real},t})$.	dimensionless
Y_t	Societal stress; three-regime update using ΔX_t and κ_t (Eq. 5.8).	dimensionless
$Y_{\text{limit},t}$	Carrying ceiling; responds to military burden, Ω_t, negative ΔX_t, and disturbance ε (Eq. 5.10).	dimensionless, ≥ 0
S_t	Crisis pool; accumulates overshoot ($Y > Y_{\text{limit}}$) or decays at rate λ_S (Eq. 5.11).	dimensionless, ≥ 0
$I_{\text{reset},t}$	Resilience reset indicator $\mathbb{I}\{S_t \geq Y_{\text{limit},t}\}$ (Eq. 5.12); application-specific downstream effect.	$\{0, 1\}$

6.2 Derived Indicators and Composites

Symbol	**Definition / Role**	**Unit / Range**
$\text{KWPE}_t^{\text{human}}$	Human labor equivalent: $130 \cdot Pop_t/10^6$ (Eq. 1). Prevents "capacity to zero" and stabilizes early-period runs.	million kWh
PE_t	Total primary energy input.	million kWh
AP_t	Animal power converted to energy.	million kWh
$PatentDensity_t$	Patent count per million people: $PatentCount_t/Pop_t \times 10^6$.	patents / million
$X_{\text{bonus},t}$	Innovation dividend (Eq. 3): multiplicative gains from STEM, education, TFP, patent ratio, and capacity ratio^P.	dimensionless
$X_{\text{bonus,norm},t}$	Clipped innovation dividend $\text{clip}(X_{\text{bonus}}, 0, 5)$; prevents unstable divergence.	$[0, 5]$

$Z_{c,t}$	Social complexity (Eq. 7): bounded mean of Gini, $\sqrt{2}$ -weighted murder / poverty, MCap cap / GDP, distrust, urban-land density proxy.	$[0, 5]$
$S_{\text{murder},t}$	Homicide proxy after scaling and $\sqrt{2}$ weight (Eq. 4).	$[0, \infty)$ (scaled to $[0, 1]$ before averaging)
$S_{\text{poverty},t}$	Poverty proxy after scaling and $\sqrt{2}$ weight (Eq. 5).	$[0, \infty)$ (scaled to $[0, 1]$ before averaging)
$MCapGDP_t$	Market capitalization as share of GDP; capped at 3 and then normalized by 3 (Eq. 6).	ratio, limit
$Trust_t$	Social trust (based on surveys). Enter Z_c as $1 - Trust_t$.	$[0, 1]$
$PeoplePerHa_t$	Population per arable hectare $Pop_t/ArableLand_t$ (Eq. 8).	people / ha
$Spopdens_t$	Urban–land pressure proxy $\text{scale}_{[0,1]}(UrbanRate_t \cdot \ln(1 + PeoplePerHa_t))$ (Eq. 9).	$[0, 1]$
Ω^*_t	Unclipped vulnerability composite (Eq. 10): $-\text{Savings} + \sqrt{2} \cdot \text{Unemployment} + \text{Debt} - \text{LPI}/10$.	real
Ω_t	Vulnerability after shock and clipping to $[-5, 5]$ (Eq. 11). Conditions Y_{limit}.	$[-5, 5]$
relax_t	Social-cushion mean of available coverages Health Care, Pension, FreeEdu, UnempIns; fall back to SocSecIndex.	$[0, 1]$
$\tilde{Z}_t$	Linear net-tension mixture: $Z\text{Shock} - \text{relax} + \gamma_S Z_c - \gamma_X X_{\text{bonus,norm}} + \text{Drift}$ (Eq. 12).	real
$Z_{\text{eff},t}$	Net tension after clip ($\pm Z_{\max}$), rescale ($\pm Z_{\text{scale}}$), and sign-preserving quadratic (Eqs. 13–15).	real
$KWPE_{pc,t}$	Per-capita energy-equivalent capacity (Eq. 16).	kWh / (person·yr)
$PopPressure_t$	Population pressure $(L \cdot PeoplePerHa)/KWPE_{pc}$ with guards (Eq. 17). Amplifies ΔX-to-Y translation.	≥ 0

6.3 Parameters and Hyperparameters

Symbol	**Interpretation / Use**	**Default / Range**
a_0, a_1, b_1, μ	Baseline stress coefficients in Y_{base}.	tuned; real

k_Y	Base gain from ΔX to Y increment (Eq. 5.8).	> 0
ZImpactK	Modulation strength of Z_{eff} in gain κ_t.	≥ 0
k_{limit}	Scale from base capacity to carrying ceiling (Eq. 5.10).	> 0
β	Decay strength for Y_{limit} under $\Delta X < 0$ (Eq. 5.10).	≥ 0
ε	Small perturbation added to Y_{limit} to avoid degeneracy (Eq. 5.10).	small > 0
λ_S	Crisis-pool decay rate when $Y \leq Y_{\text{limit}}$ (Eq. 5.11).	$(0, 1)$
θ	Innovation-dividend scale (Eq. 3).	> 0
P	Elasticity exponent linking capacity growth to innovation dividend (Eq. 3).	≥ 0
γ_S	Weight on structural complexity in $\tilde{Z}$ (Eq. 12).	≥ 0
γ_X	Weight on dividend counter-term in $\tilde{Z}$ (Eq. 12).	≥ 0
L	Land-capacity coefficient in PopPressure (Eq. 17).	15 kWh/(person·yr)
$Z_{\max}$	Theoretical clip for $\tilde{Z}$ before rescaling (Eq. 13).	7
Z_{scale}	Target symmetric bound for rescaled Z (Eq. 14).	1.4

6.4 Exogenous Shocks and Policy Levers

Symbol	**Definition / Semantics**	**Unit / Range**
$Z\text{Shock}_t$	Exogenous shock to tension channel (Eq. 12): < 0 reduces tension (good news), > 0 increases it (bad news).	real (bounded via $Z_{\max}$ pipeline)
ΩShock_t	Exogenous shock to vulnerability (Eq. 11): < 0 reduces vulnerability, > 0 increases vulnerability.	real (clipped to $[-5, 5]$)
Drift_t	Low-frequency bias term in $\tilde{Z}$; usually set to 0 in validation.	small real
MilitaryRatio_t	Military burden applied as $(1 - \text{MilitaryRatio}_t)$ to X_{norm} before Y_{limit} (Eq. 5.10).	ratio $[0, 1]$
Y_{first}	Initial anchor for Y: Used once to set the vertical level without altering the shape of the trend (Eq. 5.8).	dimensionless

6.5 Units, Normalization, and Clipping Conventions

- **Energy and capacity.** PE, AP, $\text{KWPE}^{\text{human}}$, and X_{real} are in millions of kWh. The per capita KWPE ($KWPE_{pc}$) is in kWh per person-year.

- **Normalization.** $X_{\text{norm}} = X_{\text{real}}/X_{\text{base}}$; all rate variables (e.g., coverage, trust, unemployment, savings) are scaled to $[0,1]$ before composition.

- **Clipping.** Implemented at the stage of Ω (to $[-5,5]$), Z_c (to $[0,5]$), $X_{\text{bonus,norm}}$ (to $[0,5]$), and $\tilde{Z}$ (to $\pm Z_{\text{max}}$); subsequently, $\tilde{Z}$ is rescaled to $\pm Z_{\text{scale}}$ and is quadratically amplified with preserved sign.

- **Signs and semantics.** $Z\text{Shock} < 0$ (good), $Z\text{Shock} > 0$ (bad); $\Omega\text{Shock} < 0$ (good), $\Omega\text{Shock} > 0$ (bad). Military burden *reduces* usable capacity through $(1 - \text{MilitaryRatio})$.

6.6 Missing-Data Handling (Implementation Note)

- **Availability-aware averaging.** For Z_c and relax, the engine averages only over available sub-indicators; if granular coverage data are unavailable, relax falls back to a composite Social Security Index.

- **Temporal gaps.** When constructing ratio terms (e.g. $PatentDensity_t/PatentDensity_{t-1}$, $X_{\text{real},t}/X_{\text{real},t-1}$), guard conditions avoid division by zero; Practical implementations may use LOCF/nearest interpolation for isolated gaps.

- **Safety floors.** Non-negativity is enforced for capacities and pools; perturbations like ε avoid degenerate ties.

7 Limitations and Intended Use

7.1 Non-Predictive Nature

SECM V0.5 ALPHA is designed for analytical exploration rather than deterministic forecasting. The model outputs should be interpreted as structured reflections of the interactions between productive capacity, social complexity, vulnerability, and capacity limits, given a specific set of inputs and parameters. They do not represent certainties about future events.

7.2 Data Dependency and Proxy Requirements

The reliability of SECM outputs depends heavily on the quality and representativeness of the input data. Although default variables are selected for their accessibility and relevance, users are encouraged to replace them with context-specific indicators when better alternatives are available. For historical or anticipatistical periods, proxies may be necessary (e.g., archaeological yield estimates for agricultural productivity, or historical tax records for economic output). Identifying and validating such proxies is the responsibility of the user. The author does not provide such datasets and makes no claims about their accuracy.

7.3 Societal Overload and Recovery Dynamics

The Crisis Pool (S_t) and Resilience Reset (I_{reset}) components are included to provide users with a more intuitive view of the cumulative societal overload and potential recovery capacity. However, the magnitude of overload a society can tolerate and the mechanisms by which it recovers vary greatly between cultures, governance systems, and historical contexts.

The overload decay rate and reset functions in SECM are intentionally generic, serving as conceptual placeholders rather than prescriptive formulas. Users must adapt these elements to their research context, defining appropriate decay rates, reset triggers, and recovery magnitudes based on empirical or historical evidence relevant to the society under study.

7.4 Time-Agnostic Structure

SECM operates in discrete computational steps tied to changes in productive capacity (X), not to calendar years. The length of each step is determined solely by the time resolution of the input data. This feature enables flexible application to both modern datasets and historical reconstructions, but also means that the model cannot directly account for short-term fluctuations within a given input interval.

7.5 Development Status

This version, V0.5 ALPHA, remains in active development. Formulae, parameters, and variable definitions are subject to refinement as additional testing, validation, and theoretical advancements are incorporated.

8 Conclusion

The Societal Evolution Computational Model (SECM) V0.5 ALPHA represents an original modular framework for systematically exploring the interactions between productive capacity, social complexity, systemic vulnerability, societal stress, and carrying capacity. Its architecture integrates multiple domains, including economic, social, demographic, and structural, into a coherent computational process, allowing both cross-sectional and longitudinal analysis.

A key distinguishing feature of SECM is its **time-agnostic** design, in which computational steps are driven by changes in productivity capacity rather than fixed calendar intervals. This allows the model to operate flexibly across modern datasets, historical reconstructions, and counterfactual scenarios, provided that the input intervals are consistent.

Although SECM provides a detailed and interconnected set of modules, including the Crisis Pool and Resilience Reset mechanisms, it is not a predictive 'crystal ball'. The model is intended for hypothesis testing, scenario exploration, and comparative analysis, not for forecasting specific future events. Its results should be interpreted as structured expressions of the relationships between chosen variables, within the limitations and assumptions of the framework.

The ongoing development will focus on expanding variable options, refining functional forms, and improving validation in diverse historical and cultural contexts. The present version should be regarded as an evolving research tool rather than a finalized or definitive model.

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10 References

Meadows, H. H., Meadows, L. L., Randers, J., & Behrens, W. W. (1972). *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind.* Universe Books.

Tainter, J. A. (1988). *The Collapse of Complex Societies.* Cambridge University Press.

Smil, V. (2017). *Energy and Civilization: A history.* The MIT Press.

Romer, P.M. (1990). Endogenous technological change. *Journal of Political Economy, 98*(5, Part 2), S71–S102. https://doi.org/10.1086/261725

World Bank. (2023). *World Development Indicators.* Retrieved from `https://databank.worldbank.org/source/world-development-indicators`

United Nations Development Program. (2022). *Human Development Report 2022: Uncertain Times, Unsettled Lives.* Retrieved from https://hdr.undp.org/

OECD. (2023). *OECD Data.* Retrieved from https://data.oecd.org/