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Integrated System-Dynamics and Multi-Objective Optimization of Sustainable Development Goal Interdependencies and Cross-Sector Policy Interventions

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Abstract: The Sustainable Development Goals (SDGs) form an indivisible agenda, yet policy design and implementation remain dominated by sector-specific programmes that can generate unrecognized spillovers, delayed effects and burden shifting. This study develops a dynamic systems-of-systems (SoS) decision-support framework that represents all 17 SDGs as operationally distinct but interdependent constituent systems. The framework integrates a signed and directed interaction matrix, causal-loop analysis, stock-flow system dynamics, seven cross-sector policy levers, constrained multi-objective optimization and Monte Carlo uncertainty analysis. A transparent proof-of-concept application uses normalized goal-level states and literature-informed interaction directions to compare business-as-usual, siloed growth, green-transition, human-development and optimized SoS portfolios over 2025-2035. The optimized portfolio increases the mean normalized SDG score from 0.601 under business-as-usual to 0.710 by 2030 and from 0.693 to 0.835 by 2035. It also raises the weakest-goal score from 0.452 to 0.631 by 2030 and from 0.512 to 0.753 by 2035. In contrast, the siloed-growth scenario improves the aggregate score but depresses the weakest-goal and environmental outcomes, demonstrating that aggregate progress can conceal systemic deterioration. Network out-strength identifies SDGs 16, 4, 17, 13 and 5 as high-leverage goals. Across 1,000 uncertain parameter realizations, the optimized portfolio retains a narrow 2035 mean-score interval of 0.829-0.840. The numerical results are illustrative rather than forecasts, but they demonstrate how systems engineering can convert qualitative SDG interlinkage knowledge into an auditable, adaptive and optimization-ready policy architecture.

Keywords: *Sustainable Development Goals; Systems-of-Systems; Systems Engineering; System Dynamics; Causal-Loop Diagram; Policy Coherence; Multi-Objective Optimization; Uncertainty Analysis; Leverage Points.*

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I. INTRODUCTION

The 2030 Agenda defines 17 Sustainable Development Goals, 169 targets and an integrated plan of action for people, planet, prosperity, peace and partnership [1]. Five years before the 2030 deadline, however, the United Nations reported that only 35% of assessable targets were on track or making moderate progress, while 48% showed insufficient progress and 18% had regressed below their 2015 baseline [2]. The Global Sustainable Development Report consequently argues that incremental, isolated action is inadequate and that multiple social, economic, technological and Earth-system transformations must be coordinated simultaneously [3].

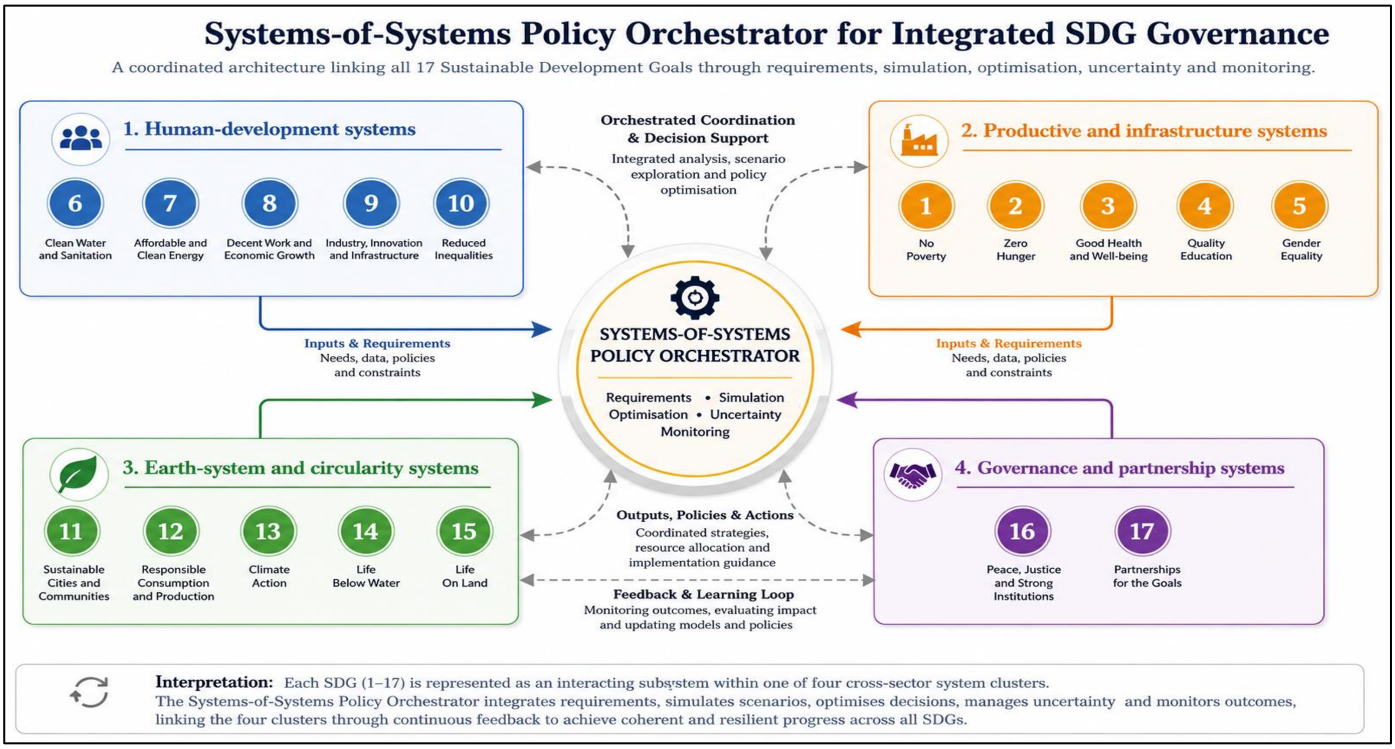

Fig 1 Graphical Abstract of the Proposed 17-Goal Dynamic Systems-of-Systems Decision Architecture.

The difficulty is not simply the number of goals. Each SDG contains targets, indicators, institutions, infrastructures, markets, ecosystems and social groups that interact across temporal, spatial and administrative boundaries. The transition from the Millennium Development Goals to the SDGs broadened the development agenda from a set of mainly social outcomes to a universal system of economic, social, environmental and institutional requirements [4]. Le Blanc demonstrated that the targets form a densely connected network [5], while Stafford-Smith et al. identified integration across sectors, actors and scales as a central implementation condition [6]. Barbier and Burgess similarly argued that sustainability must be treated as an adaptive process of balancing objectives across interdependent systems rather than as the independent optimization of sectoral goals [7].

A growing literature has mapped SD” syn’rgies and trade-offs using expert scoring, correlation analysis, network science, integrated assessment models and system dynamics. The seven-point interaction scale introduced by Nilsson et al. made direction and strength explicit [8], and subsequent studies emphasized context, directionality and indirect effects [9]. Global analyses generally find more synergies than trade-offs, but they also show that relationships vary by income, region, population group, time horizon and indicator choice [10]-[14]. Directed-network models have improved identification of influential targets [15], while system-level analyses show that indirect pathways can alter rankings derived from direct pairwise interactions [16]. Integrated assessment models extend coverage of energy, land, climate and economic feedbacks, but still do not represent the complete SDG agenda with equal depth [17].

Despite these advances, the 2024 methodological review by Assubayeva and Marco concluded that no single established method adequately combines causal explanation, directionality, dynamics, uncertainty, stakeholder knowledge and policy testing [20]. Recent systematic reviews further identify weak treatment of nonlinear mechanisms, cross-scale spillovers, uncertainty and holistic modelling of all 17 goals [23], [24]. This creates a practical gap between identifying interactions and designing an implementable, auditable portfolio of interventions under finite resources.

Systems engineering provides a relevant foundation because it begins with stakeholder needs, defines system boundaries and requirements, manages interfaces, analyses alternatives and verifies performance across a life cycle. Yang and Cormican found substantial conceptual connectivity between systems engineering and the SDGs but limited operational integration [25]. Haskins called for systems engineering methods to be applied directly to SDG implementation [26]. Industrial evidence suggests that sustainability should be treated as a system quality supported by lifecycle data and stakeholder collaboration [27], while recent energy-sector research shows the value of combining sustainability, complexity and systems thinking within one dynamic framework [28]. Acero and Ramirez Cajiao also demonstrate that causal-loop diagrams can expose reinforcing structures and leverage points in sustainability practice [29].

This article therefore proposes a dynamic systems-of-systems framework that moves beyond static interaction mapping. It treats each SDG as a constituent system with its own performance state, stakeholders and policy instruments, while a coordinating SoS layer manages interfaces, resource allocation and emergent outcomes. The study addresses three research questions: (1) how can all 17 SDGs be represented in a unified dynamic and directional architecture; (2) how can cross-sector policy portfolios be optimized while protecting

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weak goals and environmental outcomes; and (3) which goals and governance mechanisms function as high-leverage intervention points under uncertainty?

The contributions are fourfold. First, the paper translates SDG interlinkages into a signed, directed and time-dependent system-dynamics structure. Second, it connects that structure to systems-engineering requirements, interfaces, verification and decision gates. Third, it formulates a constrained multi-objective optimization that rewards aggregate progress, minimum-goal performance, environmental integrity and portfolio diversity. Fourth, it provides a reproducible proof-of-concept and uncertainty analysis that distinguishes aggregate improvement from coherent system-wide improvement.

II. LITERATURE REVIEW AND RESEARCH GAP

➢ *SDG Interactions: From Qualitative Mapping to Quantitative Networks*

Nilsson, Griggs and Visbeck proposed a seven-point ordinal scale ranging from -3, cancelling, to +3, indivisible, to characterize how progress on one target influences another [8]. The approach is valuable because it preserves direction and distinguishes enabling, reinforcing and indivisible relationships from constraining, counteracting and cancelling relationships. Later work emphasized that any score is conditional on geography, governance, technology, time and the direction of influence [9]. Consequently, an interaction should not be treated as a universal coefficient; it is a hypothesis that requires contextualization and periodic revision.

Data-driven studies use correlations among official indicators to identify recurring associations. Pradhan et al. analysed 227 countries and found that synergies generally outnumbered trade-offs, while certain goal pairs consistently generated tensions [10]. Kroll et al. examined whether countries were converting trade-offs into synergies and found positive developments around poverty, health, energy, work and infrastructure, but persistent tensions in environmental domains [11]. Lusseau and Mancini showed that the structure of the global SDG network differs by country income and is strongly influenced by inequality [12]. Warchold et al. further demonstrated variation by region, income and population group [13], and Hegre et al. identified different patterns within goals, across goals and through time [14]. These studies provide empirical association but cannot, by themselves, establish causal direction or reliably evaluate an intervention.

Network approaches respond by modelling targets or indicators as nodes and interactions as edges. Anderson et al. developed a directed systems model of target influence and showed that indirect effects can change the apparent importance of targets [15]. Dawes et al. found that rankings depend on the structure of the adopted interlinkage matrix and that system-level consequences may diverge from direct pairwise assessments [16]. Laumann et al. used network analysis to identify nexuses among the SDGs and climate action [22]. These methods are effective for prioritization, but most remain static or weakly dynamic and rarely connect target centrality to constrained policy portfolios.

➢ *Integrated Models, System Dynamics and Policy Coherence*

Integrated assessment models represent energy-economy-land-climate interactions and can quantify policy trade-offs, but their traditional scope leaves many social and institutional goals underrepresented [17]. The European Commission Joint Research Centre reviewed interlinkages and policy coherence methods and emphasized the difficulty created by multiple evolving objectives [18]. The Stockholm Environment Institute SDG Synergies approach combines expert scoring and network analysis to support cross-sector deliberation and ripple-effect assessment [19]. Kuc-Czarnecka et al. showed that conclusions regarding EU synergies and trade-offs can be sensitive to methodological assumptions [21], reinforcing the need for uncertainty disclosure.

System dynamics is particularly suited to feedback-rich policy problems because it represents stocks, flows, delays, nonlinearities and endogenous behaviour. Meadows described systems as structures whose feedbacks generate persistent patterns [30], and identified paradigms, goals, information flows and rules as high-leverage intervention points [31]. Sterman provides formal methods for causal-loop and stock-flow modelling, calibration, sensitivity testing and policy design [32], building on Forrester's foundational work on industrial dynamics [33]. Checkland's soft-systems methodology adds problem structuring and multiple stakeholder worldviews [34], while critical systems thinking emphasizes methodological pluralism, power and boundary critique [35]. General system theory supplies the wider conceptual basis for studying organized wholes and emergence [36].

Collste et al. demonstrated the iSDG family of system-dynamics models as a tool for assessing policy coherence [46]. Guerrero and Castaneda introduced Policy Priority Inference, a computational framework that models resource allocation, policy spillovers and implementation inefficiency [47], and later proposed a quantitative measure of policy-priority coherence [48]. Moallemi et al. argued that local transdisciplinary innovation is necessary for SDG implementation [49]. Allen and Malekpour integrated six transformation pathways into national systems modelling for Australia [50], while cross-scale governance research shows that transformation requires coordination among actors and levels [51]. These contributions demonstrate feasibility, but their integration with formal SoS architecture, signed goal-level networks, minimum-goal safeguards and robust portfolio optimization remains limited.

➢ *Systems-of-Systems and Systems Engineering*

A system of systems comprises autonomous constituent systems that retain operational and managerial independence while producing emergent capabilities through connectivity. Maier identified operational independence, managerial independence, evolutionary development, emergent behaviour and geographic distribution as central characteristics [37]. Boardman and Sauser added autonomy, belonging,

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connectivity, diversity and emergence as practical recognition criteria [38]. The SDG agenda exhibits these properties: ministries, markets, cities, ecosystems, communities and international institutions pursue distinct mandates, yet their combined behaviour determines national and global sustainability outcomes.

The INCOSE Systems Engineering Handbook structures the lifecycle around business and mission analysis, stakeholder needs, system requirements, architecture, design, integration, verification, validation, transition, operation and disposal [39]. ISO/IEC/IEEE 15288:2023 applies these processes recursively to systems and systems of systems [40], while the Systems Engineering Body of Knowledge provides methods for system definition, analysis, realization and management [41]. The proposed framework uses this lifecycle logic to define sustainability requirements, trace interactions, compare alternatives, document assumptions and monitor performance.

➢ *Sectoral Nexuses, Planetary Limits and Equity*

Sector-specific studies demonstrate why policy coherence cannot be inferred from aggregate growth. Fuso Nerini et al. mapped energy relationships with the full SDG agenda and showed that energy choices produce context-dependent welfare, infrastructure and environmental effects [42]. McCollum et al. similarly documented extensive energy interlinkages and the importance of governance, technology and timing [43]. Singh et al. developed a rapid assessment of co-benefits and trade-offs around ocean targets [44], while Zhang et al. showed that water-quality policy must be considered beyond a single target because water, sanitation, resources and development form an integrated system [45].

The optimization problem must also respect biophysical limits. The planetary-boundaries framework identifies critical Earth-system processes and a safe operating space for humanity [52]. The 2023 update concluded that six of nine boundaries were transgressed [53]. Purvis et al. traced the conceptual origins of the environmental, social and economic pillars and cautioned against treating them as separable [54]. Raworth's doughnut framework combines social foundations with an ecological ceiling [55], while Elkington's triple-bottom-line concept highlights simultaneous economic, social and environmental accountability [56]. Policy coherence guidance from the OECD calls for mechanisms that identify transboundary and intergenerational effects and coordinate whole-of-government action [57]. UNESCO likewise emphasizes that engineering contributes to every SDG and must address inclusion as well as technical performance [58].

➢ *Research Gap and Proposition*

The literature establishes five conclusions. First, interactions are real, directional and context dependent. Second, synergies often dominate in frequency, but a small number of trade-offs can undermine weak goals or exceed ecological limits. Third, static correlation and network models identify structure but do not fully evaluate delayed policy consequences. Fourth, system-dynamics and integrated models provide temporal analysis but differ greatly in goal coverage and transparency. Fifth, systems engineering offers lifecycle governance, yet has not been widely combined with SDG interaction science and constrained optimization. The research proposition is that a signed dynamic SoS model, governed by explicit requirements and optimized against aggregate, minimum-goal, environmental and uncertainty criteria, can improve the coherence and auditability of cross-sector policy design.

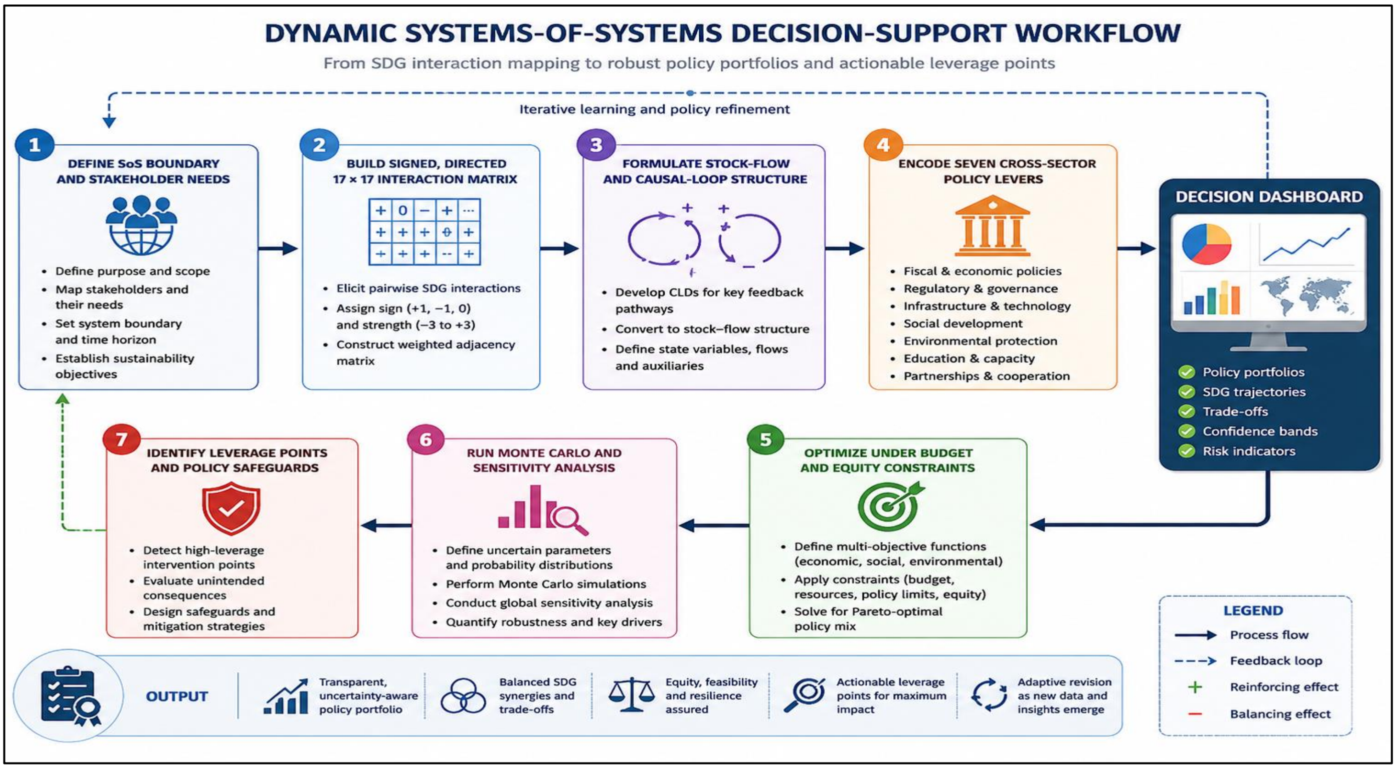

Fig 2 Seven-Stage Research and Decision Workflow for the Dynamic SDG Systems-of-Systems Framework.

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III. MATERIALS AND METHODS

➢ *Research Design and Scope*

The study adopts a design-science and proof-of-concept approach. The artefact is a quantitative decision architecture rather than an empirical forecast for a specific country. The model demonstrates how published interaction knowledge can be represented, simulated and optimized. All goal states are normalized to the interval [0,1], where 0 denotes the lowest reference performance and 1 denotes the desired target state. The 2025 United Nations assessment is used only to justify slow intrinsic progress and the need for accelerated intervention; it is not used to claim goal-specific calibration [2]. Before operational application, national indicator time series, expenditure data, stakeholder scoring and sector-model outputs must replace the illustrative parameters.

➢ *System Boundary and SoS Architecture*

The system boundary contains 17 constituent goal systems, seven policy-lever systems, a resource-allocation constraint, an interaction interface layer and a governance/monitoring layer. Each goal system has a normalized performance stock x_i(t), intrinsic improvement rate alpha_i, deterioration rate delta_i, direct policy inputs and spillovers from other goals. The constituent systems are operationally independent because progress can be pursued by different agencies and programmes; they are managerially independent because budgets and accountability are distributed; and they are evolutionarily independent because indicators, technologies and institutions change at different rates. Emergence occurs when combined interventions produce system-wide outcomes not predictable from any single programme.

➢ *Signed Directed Interaction Matrix*

A 17 x 17 matrix A represents directed interactions. Element a_ji is the annual effect of the state of source goal j on receiver goal i. Positive values represent enabling or reinforcing relationships; negative values represent constraining or counteracting relationships. The proof-of-concept matrix synthesizes recurring directions reported in interaction studies [8]-[24], energy and nexus assessments [42]-[45], and governance literature [46]-[51]. The ordinal interaction logic was rescaled to small annual normalized coefficients to maintain numerical stability. Stronger positive weights were assigned to education, institutions, partnerships, clean energy, responsible consumption and climate/ biodiversity feedbacks; negative weights represent resource pressure from conventional growth, infrastructure expansion, urbanization and food production.

The matrix contains 110 positive and 13 negative directed edges. This does not imply that trade-offs are unimportant. Negative edges are fewer but can be structurally concentrated on environmental receivers and therefore create large downstream effects. The matrix is deliberately sparse enough to remain interpretable and dense enough to demonstrate indirect propagation. For real applications, the matrix should be estimated through a triangulation of indicator time series, sector models, expert elicitation, causal evidence and stakeholder validation.

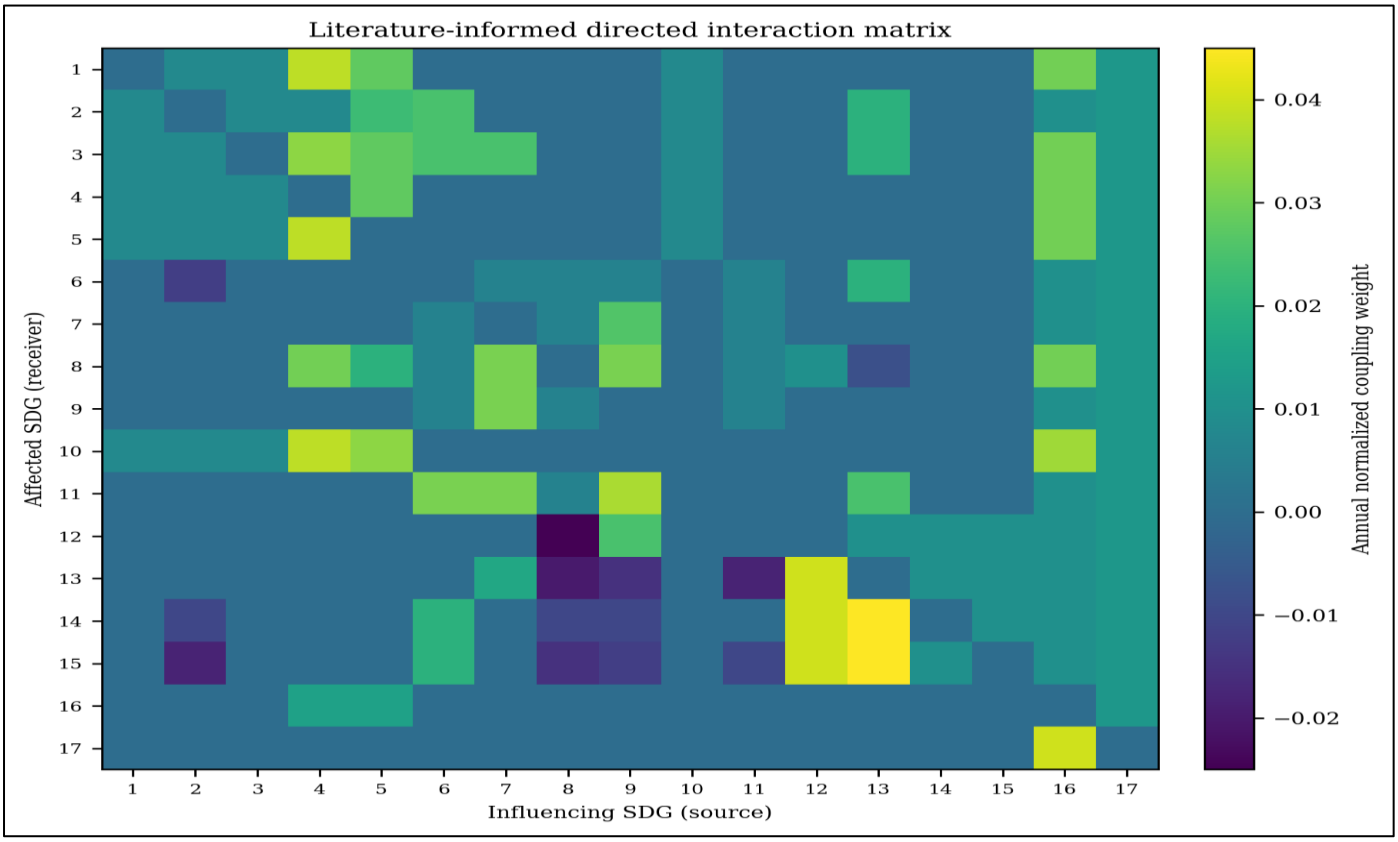

Fig 3 Signed Directed Interaction Matrix Used in the Proof-of-Concept. Positive Values Indicate Synergies; Negative Values Indicate Trade-Offs.

➢ *Dynamic Model Formulation*

Let $x_i(t)$ be the normalized performance of SDG i. Progress is bounded by a saturation term $(1 - x_i)$, so that marginal gains decline as a goal approaches its target. The state equation is:

Where alpha_i is intrinsic progress, delta_i is deterioration, a_ji is the signed interaction coefficient, b_ik is the direct effect of policy lever k on goal i, and u_k is policy intensity. This logistic interaction form is intentionally parsimonious. It captures saturation, reinforcing effects, negative spillovers and policy impulses without claiming sector-level causal detail. Numerical integration uses a 0.2-year Euler step over 2025-2035. The state is clipped to [0,1] to preserve normalized bounds.

➢ *Cross-Sector Policy Levers*

Seven levers reflect the transformation entry points emphasized by the United Nations and systems literature: food systems; clean energy; digital and industrial transformation; human capital; jobs and social protection; climate and biodiversity; and governance and partnerships. Each lever has direct positive effects on its principal goals and smaller spillovers on related goals. Selected negative coefficients represent plausible implementation risks, such as irrigation pressure, digital exclusion, rebound effects, carbon-intensive job creation and short-run adjustment costs. These risks are not fixed facts; they are safeguards that force the optimization to recognize burden shifting.

Table 1 Cross-Sector Policy Levers and Safeguarded Spillovers.

Lever	Policy system	Primary synergies	Principal trade-off or implementation risk
P1	Food systems	SDGs 1, 2, 3, 12, 13	Water demand and land conversion can weaken SDGs 6 and 15.
P2	Clean energy transition	SDGs 3, 7, 8, 9, 11, 12, 13	Poorly planned supply chains may shift pressure to water, land and minerals.
P3	Digital and industrial transformation	SDGs 4, 8, 9, 11, 16, 17	Digital exclusion and material demand may worsen SDGs 10 and 12.
P4	Human capital and equality	SDGs 1, 3, 4, 5, 8, 10, 16	Benefits depend on quality, access and institutional capacity.
P5	Jobs and social protection	SDGs 1, 2, 3, 5, 8, 10	Conventional growth may raise consumption and emissions.
P6	Climate and biodiversity	SDGs 3, 6, 11, 12, 13, 14, 15	Transition costs require just-transition and compensation measures.
P7	Governance and partnerships	SDGs 16 and 17; enabling effect on all goals	Weak accountability can dilute expenditure effectiveness.

➢ *Optimization Model*

The policy vector u is selected under a weighted budget constraint. The objective rewards mean progress, the minimum goal score, social, economic, environmental and governance performance. It penalizes cross-goal dispersion and excessive concentration of resources in a small number of policy systems. This operationalizes the principle that coherent development must improve overall performance without abandoning weak goals or ecological integrity.

$$\text{Max } J(u) = 0.42\,M + 0.20\,m + 0.12\,S + 0.08\,E + 0.10\,N + 0.05\,G - 0.10\,\sigma_x - 0.04\,\sigma_u \quad (1)$$

$$\text{Subject to: } \sum_k (c_k u_k) \le B;\ 0.15 \le u_k \le 1.00;\ 0 \le x_i(t) \le 1 \quad (2)$$

M is the mean terminal score, m is the minimum terminal goal score, S, E, N and G are social, economic, environmental and governance sub-indices, sigma_x is goal-score dispersion, sigma_u is policy concentration, c_k is relative cost and B is the available budget. Sequential least-squares programming was used to solve the constrained nonlinear problem. The lower bound of 0.15 enforces a minimum whole-of-government commitment across all policy systems.

➢ *Scenarios and Uncertainty*

Table 2 Scenario Definitions Used in the Proof-of-Concept Simulation.

Scenario	Definition
Business-as-usual	Uniform low intensity (0.05) across all levers.
Siloed growth	High digital/industrial and jobs expenditure; weak environmental and governance action.
Green transition	High clean-energy and climate/biodiversity action with moderate industrial support.
Human development	High education, health, equality, jobs and social protection expenditure.
Optimized SoS	Portfolio selected by the multi-objective model under the common budget.

Uncertainty was assessed with 1,000 Monte Carlo realizations per scenario. Interaction coefficients were perturbed with a 15% standard deviation, policy-effect coefficients with 12%, intrinsic progress with 12% and deterioration with 10%. Reported intervals are the 5th and 95th percentiles. This analysis tests structural robustness to plausible parameter variation; it does not substitute for empirical calibration uncertainty.

➢ *Verification, Validation and Interpretation Protocol*

Verification included dimensional checks, state-bound tests, zero-policy tests, time-step sensitivity and budget-feasibility checks. Behavioural validation compared model responses with established qualitative expectations: education and institutions should generate broad enabling effects; conventional growth can burden consumption, climate and ecosystems; clean energy should support health, infrastructure and climate outcomes; and integrated policy should reduce the weakest-goal deficit. The model is considered fit for its stated purpose if it reproduces these structural patterns transparently. Predictive validation is outside scope because the application is illustrative.

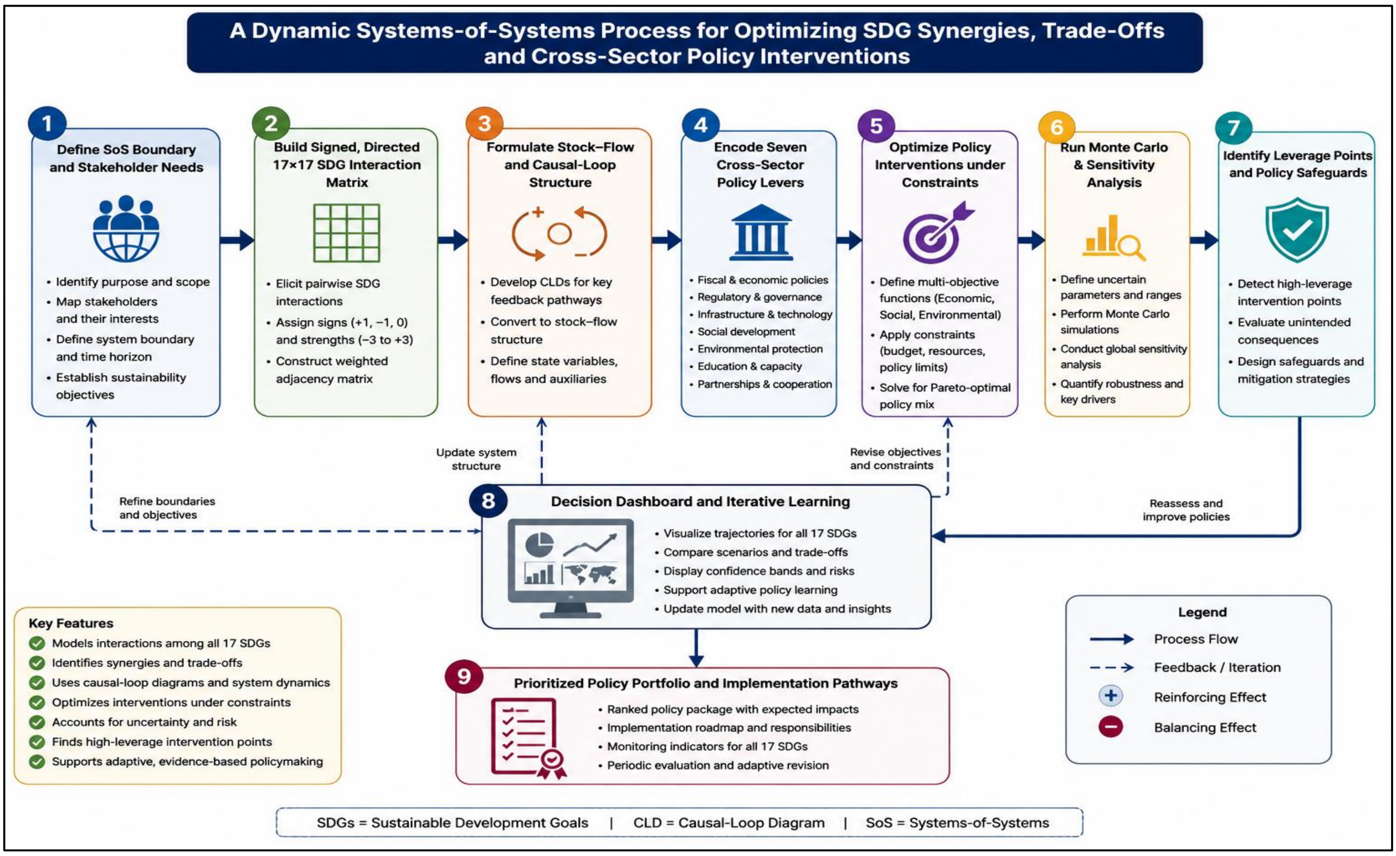

Fig 4 Reduced Causal-Loop Representation of Key Reinforcing and Balancing Mechanisms within the SDG Systems-of-Systems.

IV. RESULTS

➢ *Network Structure and Leverage Points*

The signed matrix contains a dense positive backbone and a smaller set of environmentally concentrated negative links. The strongest positive pathways include SDG 13 to SDGs 14 and 15, SDG 12 to SDGs 13-15, SDG 4 to poverty, equality and work outcomes, and SDG 16 to multiple social and governance outcomes. The strongest negative pathways arise from conventional economic expansion to responsible consumption and climate action, and from food or urban systems to water, marine and terrestrial outcomes. These patterns are consistent with the literature showing that synergies are more frequent but trade-offs can be concentrated and consequential [10]-[24].

Table 3 Highest Network Out-Strength Values in the Illustrative Interaction Matrix.

Goal	Description	Positive out	Negative out	Net out
SDG 16	Peace & Institutions	0.315	0.000	0.315
SDG 4	Education	0.200	0.000	0.200
SDG 17	Partnerships	0.192	0.000	0.192
SDG 13	Climate Action	0.185	0.008	0.177
SDG 5	Gender Equality	0.175	0.000	0.175
SDG 7	Clean Energy	0.141	0.000	0.141
SDG 6	Water & Sanitation	0.139	0.000	0.139

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SDG 16 has the highest net out-strength, followed by SDGs 4, 17, 13 and 5. The result should not be interpreted as a universal ranking. It shows that, under the adopted structure, institutional capacity, education, partnerships, climate action and gender equality propagate benefits through many pathways. These goals are candidate leverage points, but their effectiveness depends on implementation quality and the receiving systems' absorptive capacity.

➢ *Optimized Policy Portfolio*

The common budget is fully used by the optimized portfolio. The solution allocates the highest intensities to climate and biodiversity and to governance and partnerships, followed by human capital and clean energy. Minimum intensities are retained for food systems, digital/industry and jobs/social protection. This does not imply that the latter sectors are unimportant; rather, their indirect benefits and modeled trade-offs make the marginal system-wide return of additional expenditure lower after the minimum commitment is satisfied.

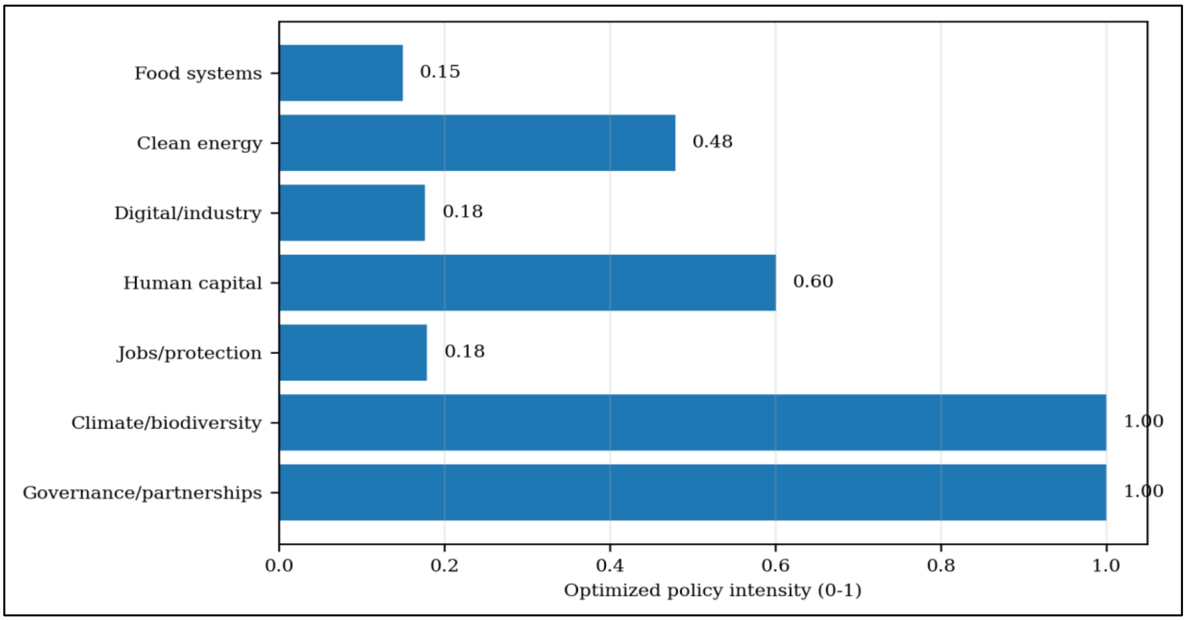

Fig 5 Optimized Cross-Sector Policy Portfolio Under the Common Normalized Budget Constraint.

➢ *Dynamic Scenario Performance*

Figure 6 shows the mean SDG trajectory. Business-as-usual improves slowly because intrinsic progress and positive spillovers remain active, but the path is insufficient for rapid convergence. Siloed growth increases the mean more quickly than business-as-usual, yet its environmental and weakest-goal performance deteriorate. The green-transition and human-development scenarios each outperform business-as-usual but display different distributions. The optimized SoS portfolio provides the highest mean trajectory and the smallest gap between strong and weak goals.

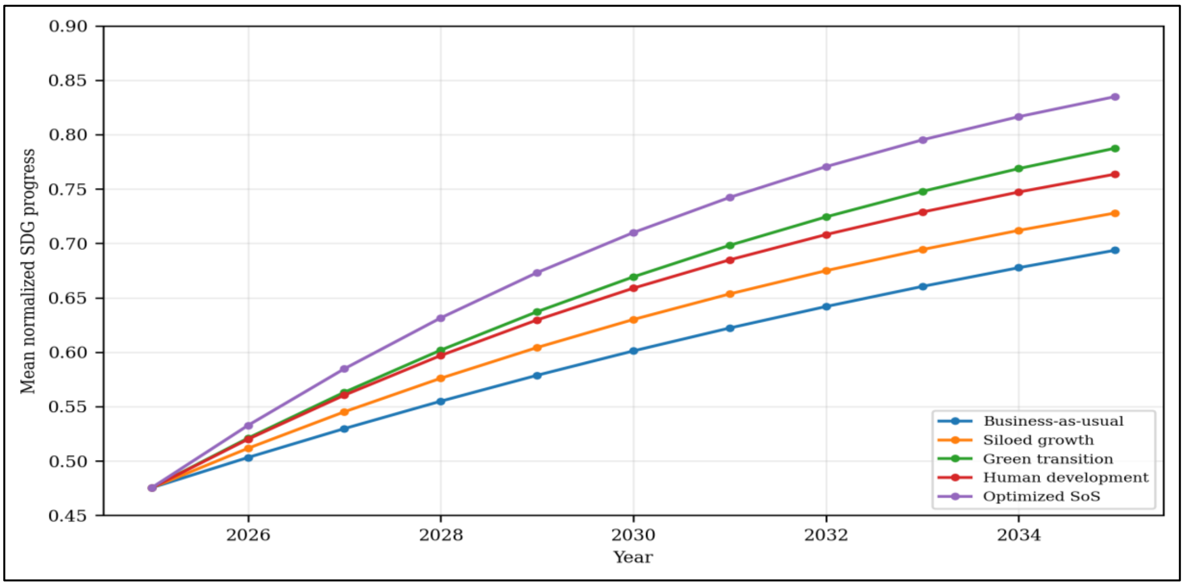

Fig 6 Mean Normalized SDG Progress Under Five Policy Scenarios, 2025-2035.

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Table 4 Deterministic Scenario Outcomes.

Scenario	2030 mean	2030 min.	2030 env.	2035 mean	2035 min.	2035 env.	Dispersion	Goals >=0.80
Business-as-usual	0.601	0.452	0.514	0.694	0.512	0.587	0.096	3
Siloed growth	0.630	0.440	0.505	0.728	0.486	0.570	0.123	6
Green transition	0.669	0.579	0.626	0.787	0.676	0.753	0.068	6
Human development	0.659	0.487	0.533	0.764	0.571	0.620	0.113	7
Optimized SoS	0.710	0.631	0.667	0.835	0.753	0.801	0.045	14

By 2030, the optimized portfolio produces a mean score of 0.710 compared with 0.601 under business-as-usual. More importantly, it raises the minimum score from 0.452 to 0.631. By 2035, the mean reaches 0.835, the minimum 0.753 and the environmental sub-index 0.801. Fourteen goals exceed 0.80. Siloed growth reaches a 2035 mean of 0.728, but its minimum score falls to 0.486 and its environmental sub-index to 0.570. The result demonstrates a central policy lesson: an aggregate index can improve while the system becomes less balanced and more environmentally vulnerable.

➢ *Goal-Level Distribution and Trade-off Visibility*

The goal-level comparison in Figure 7 reveals why minimum-goal and dispersion terms matter. Siloed growth generates high scores in energy, work, industry and selected urban outcomes but leaves environmental and equality-related systems behind. The optimized SoS portfolio improves every goal relative to business-as-usual and avoids the deep environmental trough created by conventional growth. This does not eliminate trade-offs; it offsets them through complementary policies, institutional safeguards and a diversified portfolio.

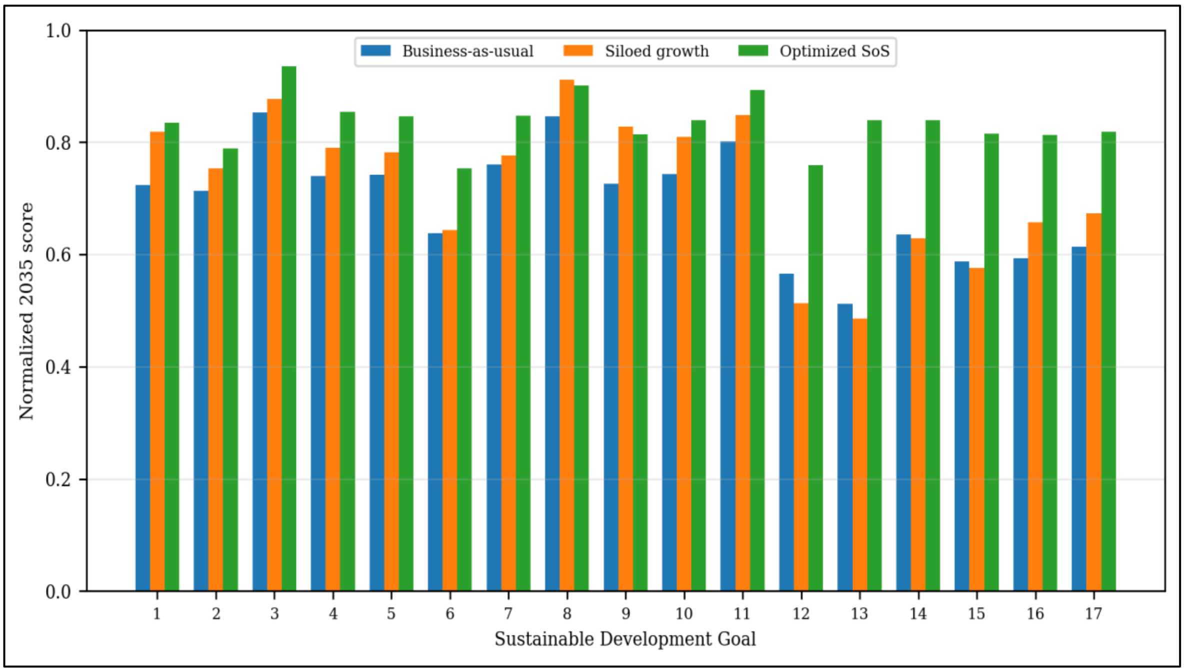

Fig 7 Goal-Level 2035 Outcomes Under Business-as-Usual, Siloed Growth and the Optimized Systems-of-Systems Portfolio.

➢ *Robustness Under Uncertainty*

Table 5 Monte Carlo Results from 1,000 Parameter Realizations Per Scenario.

Scenario	Mean	P05	P95	Expected min.	Expected env.
Business-as-usual	0.693	0.687	0.700	0.511	0.587
Siloed growth	0.728	0.721	0.734	0.482	0.569
Green transition	0.787	0.782	0.793	0.674	0.752
Human development	0.763	0.757	0.769	0.564	0.619
Optimized SoS	0.835	0.829	0.840	0.748	0.801

The optimized portfolio remains dominant across the uncertainty ensemble. Its 2035 mean score has a 5th-95th percentile interval of 0.829-0.840, compared with 0.687-0.700 for business-as-usual and 0.721-0.734 for siloed growth. The relatively narrow intervals reflect the model's bounded states and diversified policy structure. The expected minimum score remains 0.748, indicating that the fairness safeguard is not dependent on one exact parameter set.

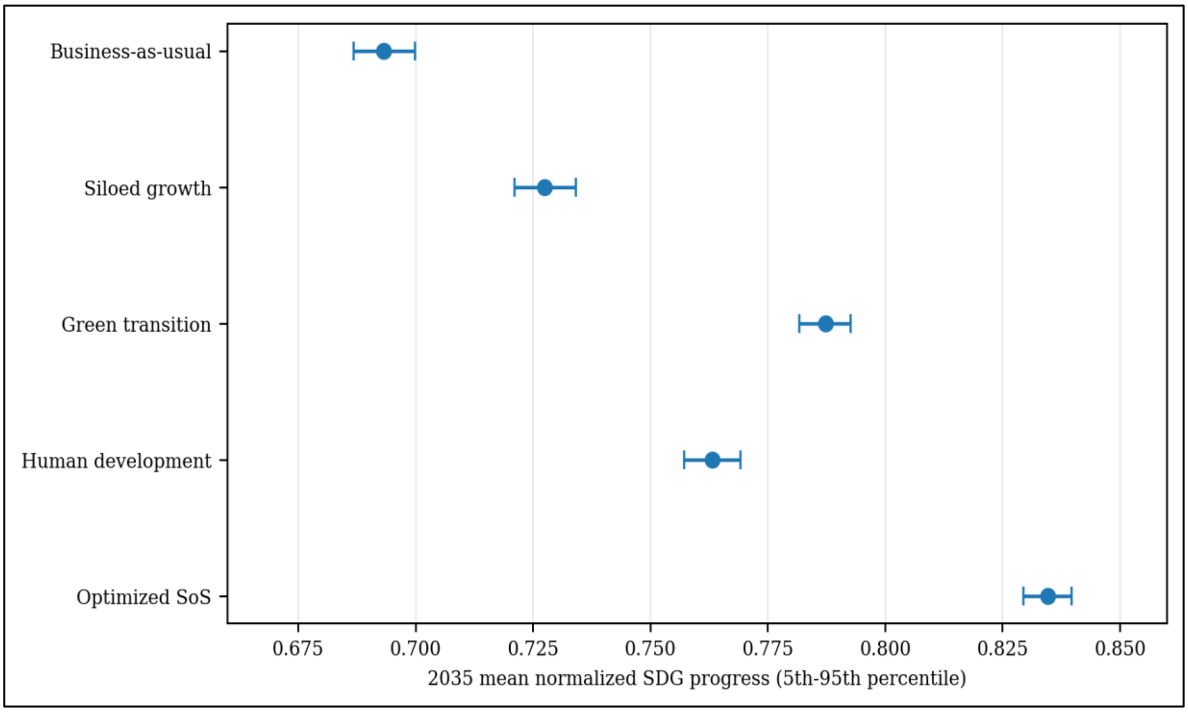

Fig 8 Monte Carlo Uncertainty Intervals for Mean 2035 SDG Performance.

V. DISCUSSION

➢ *From Interaction Maps to Policy Architecture*

The framework addresses a recurring limitation in the SDG literature: the distance between documenting interlinkages and selecting coherent interventions. Static maps answer where interactions may exist. The proposed SoS architecture adds five decision functions: requirements traceability, directional dynamic simulation, resource-constrained optimization, minimum-goal protection and uncertainty reporting. This combination enables decision makers to ask not only whether two goals interact, but how a portfolio changes the trajectory of the entire system and which safeguards are required.

The results support the proposition that policy coherence is not equivalent to equal spending or maximum aggregate progress. Siloed growth raises the mean score but worsens the weakest goal and environmental performance. This resembles real policy situations in which infrastructure, industrialization or short-run employment gains increase resource demand and emissions. The system may appear successful when evaluated through GDP or a composite average while ecological or distributional subsystems deteriorate. A coherent objective must therefore include lower-tail performance, not only the mean.

➢ *Interpretation of Leverage Points*

SDG 16 emerges as the strongest leverage point because institutional quality affects data, public finance, implementation capacity, justice and accountability across all sectors. This aligns with Meadows' emphasis on rules, information and system goals [31] and with policy-coherence guidance [57]. SDG 4 is highly influential because education strengthens health literacy, gender equality, productivity, innovation and participation. SDG 17 increases connectivity, financing, technology transfer and collective learning. SDGs 13 and 12 protect the environmental foundation on which food, health, water, cities and economic activity depend. The leverage ranking therefore combines enabling institutions, human capability and ecological stability rather than selecting a single technology.

➢ *Systems-Engineering Implications*

The SDGs can be treated as high-level stakeholder requirements that must be decomposed into measurable national and sector requirements. Interfaces between ministries and systems should be documented in an interaction register analogous to an engineering interface-control document. Policy alternatives should pass verification gates for data quality, budget feasibility and regulatory compliance, and validation gates for stakeholder value, equity and environmental integrity. A model-based systems engineering implementation could connect requirements, causal assumptions, indicator data, scenarios and decisions in a common digital thread.

The SoS perspective also clarifies governance. No central authority fully controls all constituent systems. The coordinating function must therefore rely on negotiated requirements, shared data, incentives, standards, feedback and adaptive review. This is consistent with the managerial independence of SoS constituents [37], [38]. The orchestrator should not replace sector expertise; it should expose dependencies and coordinate decisions that would otherwise be made in isolation.

➢ *Policy and Industrial Applications*

National governments can use the framework during medium-term expenditure planning, climate and development strategy preparation, and review of national SDG roadmaps. Cities can adapt the state variables to urban indicators and

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model housing, mobility, energy, water and health interactions. Industries can use the architecture to test how capital projects contribute to or burden SDG outcomes across supply chains. Development banks can integrate the objective function into portfolio appraisal, while regulators can require explicit trade-off registers and mitigation plans for major cross-sector programmes.

For developing and emerging economies, the method can support prioritization under severe fiscal and data constraints. It is particularly useful where rapid industrialization, energy access, food security and urban growth must be pursued without locking in high emissions or ecosystem damage. The model can also test just-transition packages by linking decarbonization to employment, social protection, education and regional development. Because the coefficients are context dependent, participatory calibration is essential; imported interaction matrices should never be treated as universal truth.

- *Comparison with Existing Approaches*

Compared with expert interaction scoring, the framework adds temporal trajectories and optimization but requires more assumptions. Compared with correlation and network analysis, it adds causal hypotheses and policy testing but cannot infer causality from data alone. Compared with integrated assessment models, it offers broader goal coverage and simpler transparency but less sectoral detail. Compared with iSDG and PPI, it makes the SoS architecture, signed goal-level interaction matrix, minimum-goal criterion and environmental safeguard explicit. The framework is therefore complementary rather than a replacement: national implementation should link it to detailed energy, land, macroeconomic, health, water and fiscal models.

VI. LIMITATIONS AND FUTURE RESEARCH

The first limitation is parameterization. The interaction matrix is literature informed. Second, each goal is represented by one normalized stock, which conceals target-level heterogeneity and distributional differences within countries. Third, the logistic equation simplifies threshold effects, path dependence, political feedback, technological learning and shocks. Fourth, the optimization weights embody normative choices. Different stakeholders may assign different importance to the mean, minimum, environment, equality or portfolio diversity.

Future research should estimate directed and time-varying interactions at indicator level using causal inference, Bayesian networks, lagged panel models and expert elicitation. The model should be coupled with sectoral simulators and spatial data to represent transboundary spillovers and subnational inequality. Distributionally robust or stochastic optimization could incorporate deep uncertainty, while multi-actor game models could represent political economy and implementation behaviour. A model-based systems-engineering platform should provide version control, assumption traceability, dashboards and continuous updating from official SDG data. Validation should include participatory workshops, historical back-testing and comparison against alternative model structures.

A particularly important extension is the explicit integration of planetary boundaries and social foundations as hard or soft constraints. This would prevent an optimization from achieving high SDG scores through pathways that exceed ecological limits. Another extension is adaptive policy sequencing: investments in institutions, data and education may need to precede capital-intensive transformations because they increase the effectiveness of later expenditure. Finally, post-2030 research should examine how the SDG architecture can evolve without losing the integrated, universal and equity-oriented principles of the 2030 Agenda.

VII. CONCLUSION

This study develops a dynamic systems-of-systems framework for optimizing SDG synergies, managing trade-offs and evaluating cross-sector policy interventions. The framework represents all 17 goals as autonomous but connected constituent systems and combines signed interactions, causal-loop reasoning, system dynamics, constrained multi-objective optimization and Monte Carlo uncertainty analysis. The proof-of-concept demonstrates that aggregate improvement is an insufficient criterion: a siloed growth strategy can raise the mean score while weakening the lowest-performing and environmental goals. The optimized portfolio achieves higher average progress, stronger minimum-goal performance, lower dispersion and improved environmental outcomes.

The central practical implication is that sustainable-development planning should be managed as an evolving SoS rather than a collection of sector programmes. Institutions, education, partnerships and ecological safeguards are leverage points because they modify the performance of many constituent systems. A publishable empirical application will require country-specific indicator data, participatory interaction scoring, sector-model coupling and historical validation. Nevertheless, the architecture provides a transparent bridge between systems engineering and SDG policy science and offers a disciplined basis for designing coherent, adaptive and auditable development portfolios.

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- *Data Availability and Reproducibility Statement*

The model equations, initial states, policy definitions and optimization criteria are reported in the manuscript. The numerical parameters are illustrative and are intended to demonstrate the framework.

- *Conflict of Interest*

The author declares no conflict of interest.

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