From Complex SDG Systems to Network Models: an Ontology-Based Eight-Step Framework

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Abstract

With only 18% of Sustainable Development Goals (SDGs) on track for 2030, systems-based approaches to understanding their interdependencies are essential. Network science can reveal leverage points and guide prioritisation, yet it is often applied without sufficient domain integration, obscuring rather than clarifying sustainability dynamics.

We present an eight-step framework for evaluating network science applications in SDG research, applied to 25 studies. The analysis reveals two dominant patterns: semantic/expert-based approaches (11 studies) and indicator/statistical approaches (12 studies). Beyond these, one study implements a multiplex design and one a heterogeneous multilayer architecture. Critically, 96% focus on formal SDG structures rather than the actors, processes, and mechanisms through which targets are achieved, limiting practical utility.

The framework makes explicit how modelling choices encode theoretical assumptions and supports like-with-like comparison, meta-analysis and evidence synthesis. As AI-enabled knowledge synthesis proliferates, such transparency steers SDG modelling toward implementation-relevant representations that preserve contextual factors shaping real-world transformations.

Keywords: SDG, Network science, Complexity.

Introduction

Achieving the SDGs requires more than isolated progress on individual targets. It depends on understanding how goals interact and how progress in one area generates ripple effects, both positive and negative, across interconnected systems [1]. For instance, biodiversity loss and climate change are increasingly recognized as outcomes emerging from social and ecological interactions[2], potentially impacting food security and community well-being. Analytical efforts to map SDG interlinkages have grown in recent years, with comprehensive overviews provided [3, 4 5], translation into practices remains limited [6 7]. A science-based understanding of how synergies and trade-offs emerge is critical for making the SDGs operational in real-world contexts [8], particularly with the 2030 deadline approaching rapidly: as of 2025, only 35% of targets show adequate progress (18% on track, 17% making moderate progress), while 48% show insufficient progress and 18% have regressed below 2015 levels [9](UN DESA, 2025).

This becomes increasingly important in light of scenario-based planning frameworks [10] and transformation-oriented strategies [11]. Without adequate grounding in sustainability pathways, models may oversimplify system dynamics [12].

Network science provides valuable tools to reveal and structure such interactions, yet its application to sustainability challenges remains methodologically fragmented. Unlike traditional disciplinary applications where network elements and relationships are well-established, sustainability research requires integration of multiple disciplinary perspectives, like ecological connectivity and institutional arrangements, into coherent network representations [13]. The challenge proves particularly evident in SDG research. Most network analyses treat goals, targets or indicators as abstract nodes, often without representing the mechanisms through which sustainability transformations occur [8] [12]. In the broader literature, some studies rely on indicator correlations to define links, while others situate SDGs within governance or social–ecological systems. These differences reflect deeper theoretical questions about whether network patterns represent causes, effects or emergent properties, distinctions that shape both analytical choices and policy relevance [13]. In our sample of 25 studies, almost all abstract SDGs as targets or indicators; one specifies a multiplex structure and one links distinct SDG levels in a heterogeneous multilayer (network-of-networks) design. None model implementation actors or sectors as nodes, and no hypernetworks appear.

Translating sustainability phenomena into networks is not neutral. Abstraction requires ontological commitments about which system features matter scientifically [14]These decisions shape not only the network's structure, but its interpretive power, affecting what dynamics become visible, and which remain hidden [15]. Without domain grounding, representations may miss key processes or reinforce misleading simplifications.

We address the methodological gap limiting the effective use of network science in sustainability contexts. We propose a systematic framework that operationalizes the dual-theory approach proposed by Brandes[14], requiring explicit integration of domain expertise with mathematical theory. Our approach treats network science not as a visual tool, but as a structured method for rigorous analysis, one that can underpin evidence-based decision-making. By identifying methodological patterns across recent SDG studies, we show how lack of contextual grounding weakens comparability and limits practical value. The proposed framework supports more consistent, transparent and decision-relevant applications of network science in sustainability research. This approach also enhances reproducibility by making methodological assumptions explicit and comparable across studies.

We pursue three objectives: (1) develop and validate a methodological framework for evaluating how network science is applied; (2) demonstrate its utility by analyzing methodological patterns in selected SDG network studies; and (3) establish a foundation for meaningful cross-study comparisons that respect methodological compatibility and enable meta-analytical synthesis.

The scope of our analysis is limited to studies that examine SDG interactions through the lens of network science. Our selection excludes studies that explore broader sustainability linkages (e.g. SDGs and climate governance or resilience) unless they explicitly engage with formal network modelling [16, 17]. Our selection builds on the state-of-the-art review by Bennich[3] which identified 70 peer-reviewed studies on SDG interactions, of which only 16% applied network analysis tools. We extend this base to include more recent methodological contributions, focusing specifically on studies where network science is applied as a formal analytical approach to SDG interlinkages.

SDG as Complex Systems: The Analytical Challenge

The UN's 17 Sustainable Development Goals (SDGs), supported by 169 targets and 231 indicators, establish a universal policy framework. Yet their hierarchical structure, with indicators nested under targets, targets under goals, reflects political compromise rather than scientific logic, obscuring the interconnections the 2030 Agenda deems fundamental [18].

This has reinforced a fragmented research and policy culture where goals, targets and indicators are treated as discrete analytical units rather than parts of interdependent systems [3] [19]. Even when linked to broader sustainability domains like food systems or ecosystem services, formal system-based methodologies are rarely applied [20]. This fragmentation contributes to uneven outcomes: as of 2025, ~35% of targets show adequate progress (18% on track, 17% moderate), 48% insufficient, and 18% regressing [9]. This pattern reflects a persistent tendency to address poverty, climate, biodiversity, and inequality as discrete agendas, despite well-documented interdependencies [2122].

The SDGs exhibit the hallmarks of a complex system: multi-scale interactions, feedback loops, emergent properties, and adaptive behaviours [23]. Consider food security (SDG 2), which emerges from interactions across multiple scales: individual dietary choices, local farming practices, regional trade networks, and global climate patterns. A complex systems network representation would capture farmers as nodes linked to land parcels, credit institutions, and markets; these local networks would connect to regional commodity flows and international trade agreements; climate nodes would influence both production capacity and price volatility through feedback loops that operate on different timescales. In contrast, current approaches typically model Goal 2 as a single node connected to other goals through indicator correlations, obscuring the multi-actor, multi-scale processes that actually determine food outcomes.

Conventional tracking approaches, while useful for monitoring progress, cannot capture how interventions propagate across domains or aggregate to global effects, and studies linking SDGs to other sustainability agendas rarely apply formal complexity-informed analytical frameworks [3 20].

This analytical shortfall constrains policy design: without models that reflect the realities of implementation, decision-makers lack tools to identify leverage points, anticipate unintended consequences, or design synergistic strategies [2219]. The recent growth of research on *"SDG interactions"* signals recognition of this need, yet many approaches remain conceptually underdeveloped and methodologically inconsistent [3 20].

Here, we examine SDG interdependencies through network models, focusing on the assumptions embedded in their construction. Network science, which centers on relationships, structures and dynamics, offers a natural lens for analysing such complexity, provided sustainability phenomena are carefully translated into network form [15, 24]. By applying a structured, theory-grounded framework, we aim to advance both conceptual clarity and analytical rigour in the study of SDG linkages.

Network Science: A Scientific Method for Modelling Complex Systems

Network science provides a systematic approach that integrates domain knowledge with mathematical methods to represent and analyse complex systems, ranging from brain cell development and online social interactions to ecosystems and policy networks [2526]. This discipline is increasingly recognized for its capacity to conceptualize the intricate interdependencies characteristic of complex challenges like the SDGs [13].

Despite this potential, a persistent gap remains between theoretical advances and real-world applications [27]. This disconnect often results in methodologies that are detached from core research questions and rely on oversimplified representations of the relationships between data and network structures, which is precisely the challenge facing SDG interaction studies.

To address this gap, we develop a framework grounded in Brandes et al., 2013, who define network science as "the study of the collection, management, analysis, interpretation, and presentation of relational data." Their definition highlights two interconnected aspects of network theory: (1) domain-specific theories which abstract real-world phenomena into network concepts within specific empirical contexts, and (2) mathematical network theories which examine formal properties and statistical features independent of domain-specific content. This abstraction requires ontological commitment to scientifically relevant features, representing not a neutral technical choice but a theoretical position [14].

We propose a framework to bridge theory and practice (Figure 1).

Phase I. System Framing defines observed phenomena and research questions. **Phase II. Network Abstraction** formalizes translation of systems into network concepts. **Phase III. Network Conceptualization** specifies mathematical modelling elements, relationships, and architecture. **Phase IV. Network Analysis** applies techniques to derive domain insights. Each phase addresses a key dimension of translating complex systems into meaningful network representations.

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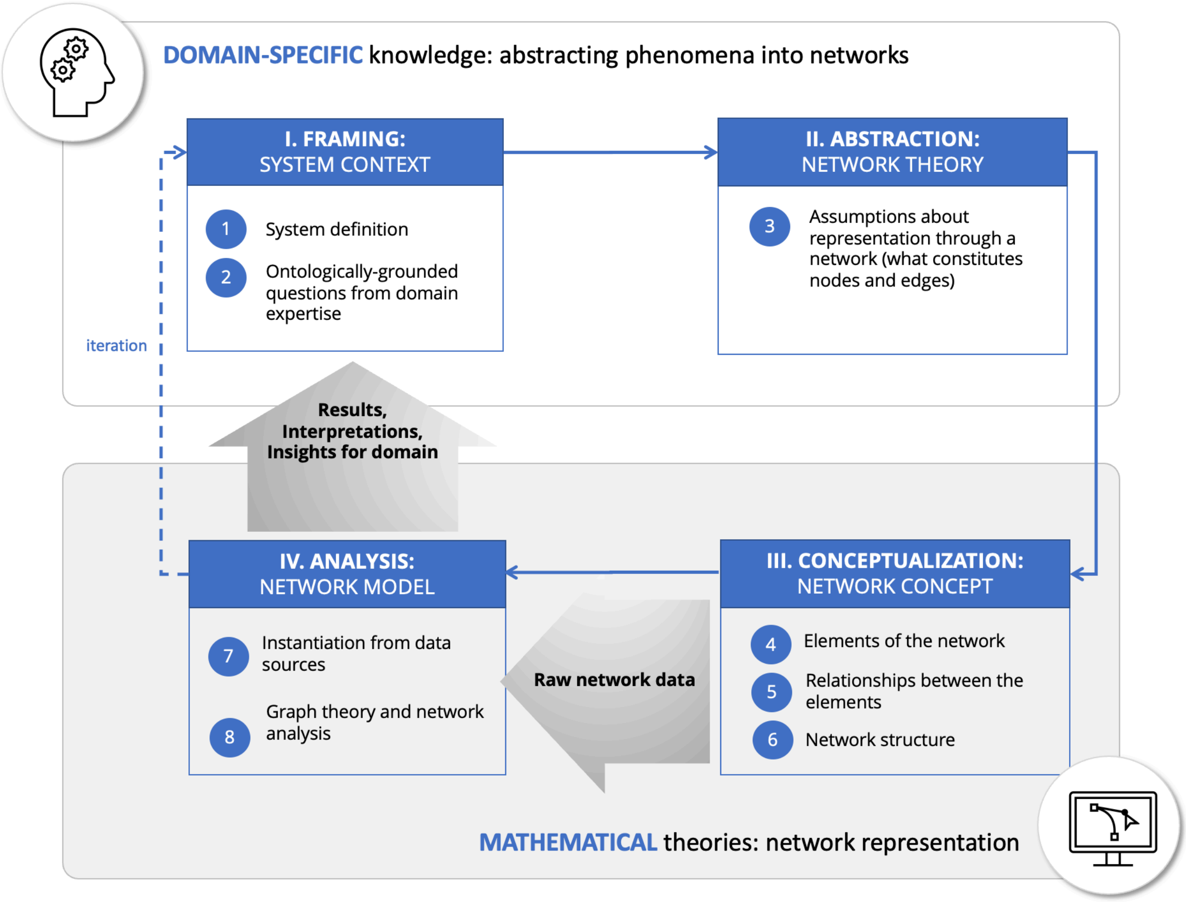

Figure 1. ***The Scientific Method for Network Modelling: From Phenomena to Network Models.***

Our framework distinguishes ***four methodological phases*** *(shown in blue boxes), each involving that require deliberate theoretical and analytical choices, and* ***two operational processes*** *(shown as grey arrows) that implement these choices without introducing new methodological decisions. Data collection operationalizes the conceptual design, while interpretation translates results back to domain insights, potentially triggering iteration.*

Phase I. Framing defines the observed phenomenon, system boundaries, and research questions suitable for network analysis, laying the groundwork for domain-specific foundations.

> **(1) System definition**: Identifying the real-world system(s) to be analysed;
>
> **(2) Ontologically grounded questions**: Formulating research questions that reflect domain-specific assumptions about entities and relations relevant to the network.

This foundational phase draws on domain expertise to determine what is meaningful to represent and analyse as a network

Phase II. Network Abstraction formalizes the translation of real-world systems into abstract network representations by linking domain understanding with network-theoretical assumptions

> **(3) Assumptions about representation:** Determining what will constitute nodes and edges, based on how the system is interpreted through network theory.

This phase captures the ontological commitments that shape the network's representational logic.

Phase III. Network Conceptualization translates abstract assumptions into mathematically precise specifications for modelling

> **(4) Elements of the network**: Defining what entities (nodes) are included.
>
> **(5) Relationships between elements**: Specifying the nature of connections (edges) among nodes.

(6) Network structure: Choosing the network's formal architecture (e.g., directed vs. undirected, weighted vs. unweighted, monoplex vs. multiplex).

This phase results in a clear conceptual model that guides data collection and network construction.

Raw network data (shown in the grey arrow between Conceptualization and Analysis) operationalizes the model into an empirical dataset. Once the conceptual structure is defined, data collection becomes a technical task, executed according to model specifications without additional methodological decisions.

Phase IV. Network Analysis applies mathematical techniques to explore the properties of the constructed network and derive insights relevant to the original domain.

(7) Theory of network representation and analysis: Selecting appropriate metrics or algorithms to analyse the network.

(8) Variables used as network data: Identifying and interpreting the data elements feeding the network model.

The goal is to reveal insights that would not be accessible without network analysis, thereby validating the modelling approach.

Results, Interpretations, Insights for domain (shown in the grey arrow pointing back) closes the loop by translating analytical findings into domain-specific understanding. This interpretive process may uncover new dynamics, refine theoretical assumptions, or expose mismatches in earlier framing decisions. When this occurs, it initiates iteration (shown by the dotted arrow), allowing for progressive refinement of both conceptual clarity and empirical fit.

Methodology: Evaluating Network Representations of SDG Phenomena

We analysed 25 peer-reviewed studies applying network science to SDG interactions, identified through systematic reviews and targeted searches. Our goal is not to grade individual studies, but to analyse the choices researchers make when translating sustainability phenomena into network form.

We introduce a three-tier classification capturing integration levels between domain knowledge and mathematical theory: Tier A (descriptive approaches), Tier B (intermediate theoretical engagement), Tier C (high conceptual alignment with formal theories). This classification captures different methodological approaches rather than a strict progression, enabling structured meta-analysis of how studies navigate the translation from domain phenomena to network concepts. We next apply this framework to a corpus of SDG network studies to characterise prevailing modelling choices (see Results).

(Detailed classification criteria and complete study analysis are provided in Supplementary Methods and Supplementary Table 1.)

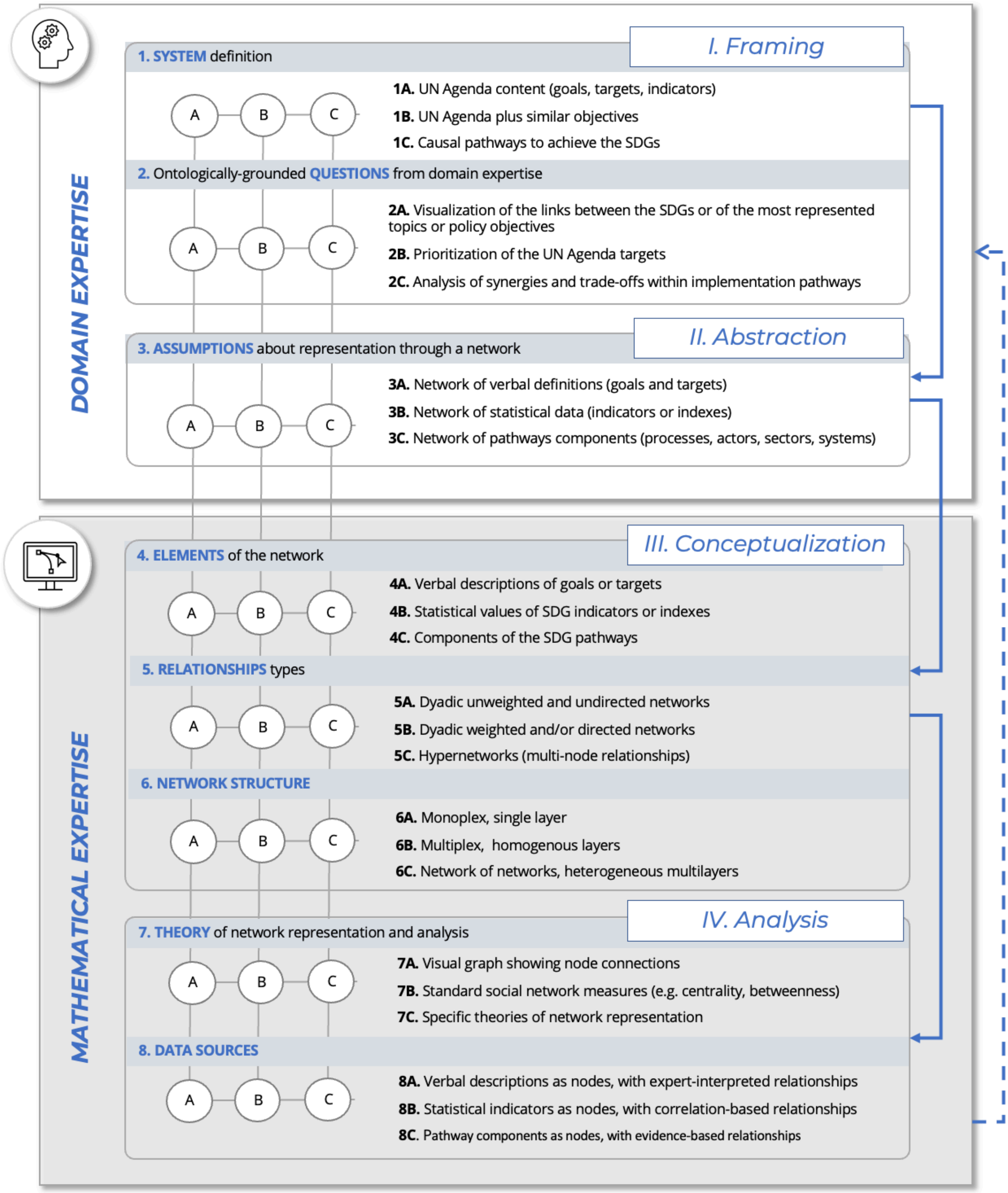

Figure 2. Classification framework for evaluating SDG network studies across four methodological phases and eight analytical steps. Tiers A, B, and C represent increasing levels of theoretical integration and implementation relevance.

Results

We applied our classification framework to 25 peer-reviewed studies that use network science to analyse interactions among the Sustainable Development Goals (SDGs). Analysis reveals two dominant patterns: semantic/expert-based approaches (11 studies) and indicator/statistical approaches (12 studies), along with two rare multilayer variants (one multiplex and one heterogeneous multilayer).

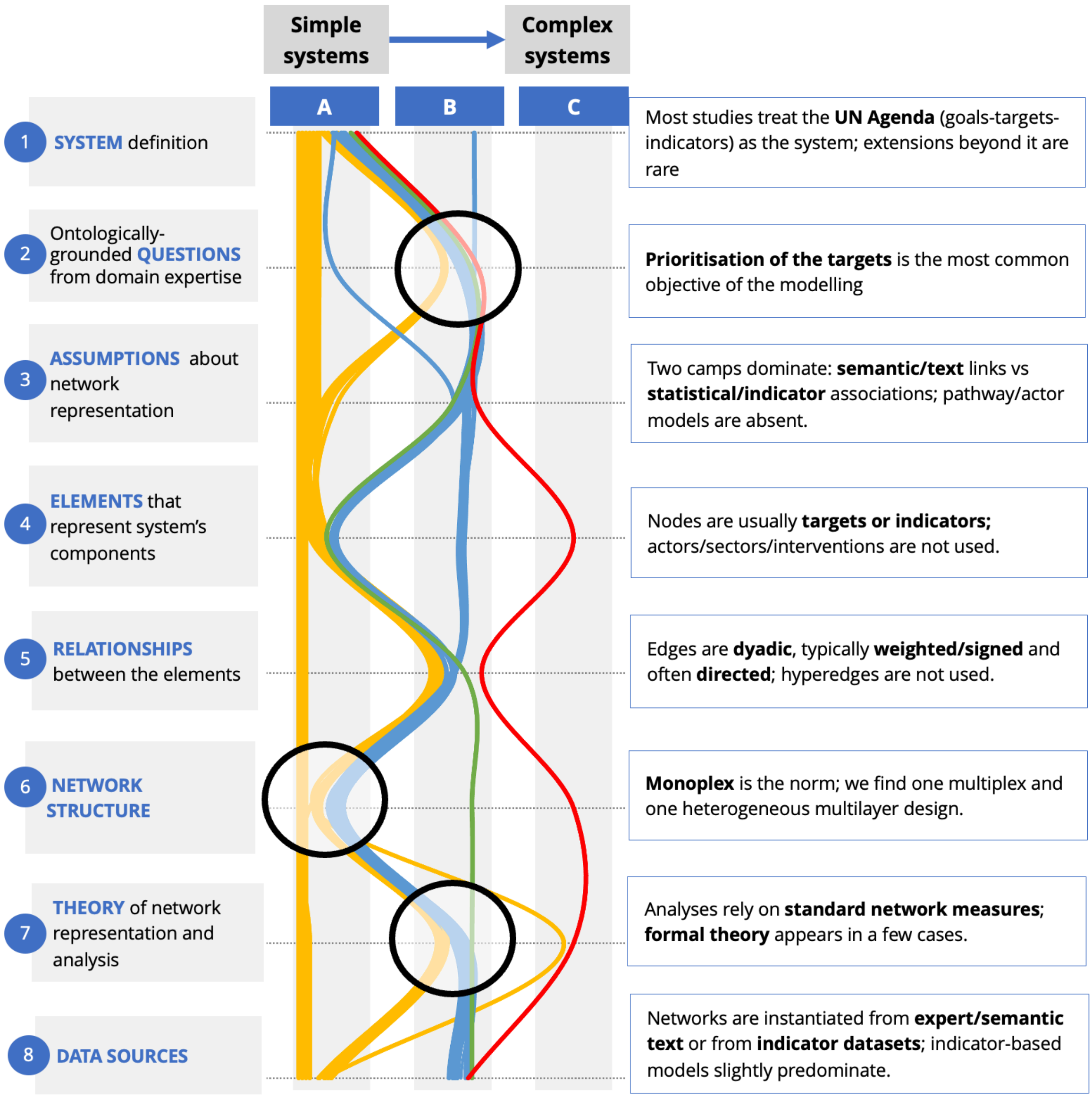

Figure 3. The classification framework reveals four patterns in approaching SDG network modelling.

Yellow pattern (expert/semantic, n=11): [28], [29], [30], [31], [20], [32], [22], [33], [34], [35], [36]

Blue pattern (indicator/statistical monoplex, n=12): [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48]

Green pattern (multiplex): [49]

Red pattern (network-of-networks): [50]

Eleven studies construct semantic networks from policy texts, using expert elicitation, keyword co-occurrence, systematic literature synthesis, and text embeddings. Twelve studies rely on indicator-based associations including correlations, Granger causality, and spatial econometrics, mostly using UN/World Bank time series. Beyond these, one study implements a multiplex architecture and one a heterogeneous multilayer "network-of-networks" linking indicators, targets and goals. Despite these differences, most papers do not explicitly justify the representational assumptions that shape how SDG systems are abstracted and analysed.

Across all categories, a striking gap: 96% of studies lack connection to real-world SDG implementation systems. This figure reflects studies' focus on the formal UN framework structure rather than the actors, technologies, and governance mechanisms that drive SDG implementation in practice. These representational choices have practical consequences for analytical validity and decision-making. When models treat SDG interactions as simple correlations between aggregate indicators, they cannot identify where investments might create cascading effects or where apparently separate goals share common bottlenecks. Models that abstract away from implementation actors and processes cannot reveal these system dependencies, leading to fragmented understanding that misses leverage points where coordinated capital allocation might achieve breakthrough results.

Analytically, semantic approaches rely on expert judgement or semantic proximity, which can limit replicability; indicator approaches apply statistical association without establishing causal mechanisms, which risks misinterpretation of coincident trends. Network structures are similarly constrained: all but two studies are monoplex, with no hypernetworks appearing despite sustainability challenges requiring multi-actor coordination and higher-order interactions.

Conclusion: From Structural Models to Systemic Insight

This analysis highlights a persistent disconnect in how network science is applied to sustainable development. While SDG interlinkages are frequently modeled, 96% of current studies focus on abstract structures rather than the mechanisms through which sustainability transformations actually occur. This disconnect between analytical form and real-world implementation limits the usefulness of these models for decision-makers, especially those allocating capital in support of sustainable outcomes.

Our framework shows that modelling choices, often presented as neutral or technical, are in fact grounded in conceptual assumptions. These assumptions shape which dimensions of sustainability systems are brought into focus and which remain unexamined. The widespread reliance on simplified approaches reflects not a lack of technical tools, but rather a limited conceptual framing of what network models are meant to capture. By making these foundations explicit, the framework supports more intentional and implementation-relevant design of network-based analyses.

Two methodological shifts are now essential. First, a move from static structural representations to process-based models that incorporate the actors, financial flows, institutional arrangements, and feedback mechanisms through which change actually unfolds. Second, the adoption of more expressive network architectures, such as multilayer and multiplex structures, enables a richer representation of interdependent systems and helps identify strategic points where interventions or investments may produce cascading effects.

Recent developments in social-ecological network (SEN) analysis further illustrate the potential of embracing a complex systems perspective. For example, the typology proposed by Sayles[51] demonstrates how multiplex, multilevel, and multidimensional network structures can be used to represent the diverse relationships among actors, institutions, resources, and ecological processes. Applying similar structural richness in SDG network research would enable more accurate representation of how sustainability outcomes emerge across domains and scales. This perspective supports models that reflect not only what goals are linked, but how implementation unfolds through interacting social, institutional, and material systems.

These improvements are not only relevant to academic modelling but are also critical for practical decision-making. Investors, multilateral development banks, and blended finance platforms increasingly require analytical tools that can identify leverage points, anticipate systemic risks and trade-offs, and demonstrate impact beyond linear performance metrics. Models built on static indicators or semantic proximity cannot meet these demands. In contrast, those grounded in causal mechanisms and implementation logic offer insight into how capital allocation in one domain may reinforce or undermine outcomes in others.

This challenge is not confined to SDG research. Similar limitations are found across domains such as climate finance, sustainable infrastructure, supply chain transitions, and nature-based solutions. In each case, network science has the potential to illuminate system dynamics, but only if it is aligned with the realities of institutional coordination and financial decision-making. The classification framework we propose offers a transferable diagnostic tool that helps assess whether models are capturing system complexity or merely replicating formal structures.

As AI-assisted meta-analysis and automated evidence synthesis become more common in investment and sustainability assessment, the risks associated with methodological opacity and structural incompatibility grow. Without transparent frameworks, combining incompatible models can lead to misleading conclusions. Our approach helps mitigate this risk by clarifying what a given network model represents, how it was constructed, and what types of questions it is suited to answer.

With fewer than five years remaining to achieve the 2030 targets, the urgency is clear. The field no longer needs models that only describe complexity. It needs tools that help decision-makers understand where to act, how to intervene, and how to direct capital toward transformations that matter. The technical capabilities are already in place. What is now required is a methodological shift to match the complexity of the systems we aim to change.

The analytical limitations translate directly into missed opportunities for strategic intervention. Complex systems exhibit non-linear responses where investments in specific network positions can produce disproportionate effects across multiple SDGs. Yet current models, focused on formal goal structures rather than implementation networks, cannot identify these high-leverage investment opportunities. When the 2030 deadline approaches with only 18% of targets on track, the field needs models that reveal where coordinated action across actors and sectors might achieve systemic change, not just which goals correlate with other goals. This becomes particularly critical as private capital increasingly seeks to demonstrate measurable sustainability impact, a need that current network approaches cannot adequately serve.

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