
Implementation-Grounded Network Science for the Sustainable
Development Goals:
The Four-Phase Implementation Network (4PIN) Framework

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PhD in Complexity Sciences

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*Dedicated to my loved ones,
whose support and resilience made this journey possible,
and to the pursuit of purpose that inspires this work.*

Acknowledgements

This PhD began long before formal enrollment, as a persistent effort to understand how systems actually function: how finance, governance, environmental reality, and human choice connect in ways that produce real outcomes. Albert-László Barabási wrote that "networks are present everywhere. All we need is an eye for them." This thesis is an attempt to develop that eye, to see structure where others see only complexity, and to trace how connections produce consequences.

My father, Serhiy, a scientist, filled my early years with conversations about natural systems, space physics, and complexity. My mother, Lyuba, taught resilience and the quiet discipline of continuing when conditions are difficult. That combination of curiosity paired with steadiness shaped everything that followed.

The first and deepest thanks go to Professor Rui J. Lopes. His guidance combined rigor, trust, and human understanding in ways that mattered enormously. He encouraged me through challenging phases and believed in the value of what I was trying to do. That support did not simply make academic progress possible, it made this entire journey more grounded and humane. I am genuinely grateful. Intellectually, this thesis stands on foundations built by others. Ulrik Brandes' work fundamentally shaped how I approach network analysis. Brandes emphasizes that the phenomenon comes first and models follow, that a network model should be viewed as yielding a representation of something, not as a structure imposed from outside. In this work, networks are not metaphors borrowed from physics or sociology, but structures built to hold the specific logic of finance, governance, and environmental systems simultaneously. That discipline, refusing to separate method from meaning, runs through every chapter.

Melanie Mitchell's writings provided essential clarity on what complexity is and what it is not. Her work consistently emphasizes that complexity is not chaos or randomness, and that understanding complex systems requires attention to how individual components interact to produce collective behavior that is not reducible to those components. This thesis attempts to honor that distinction: to engage with complexity rigorously, not decoratively, and to trace how structure produces outcomes without retreating into vague invocations of emergence or unpredictability.

Much of this thinking developed in places where theory meets reality: during field work across the Central Highlands of Vietnam, flights over uninhabited stretches of Colombia's Vichada, and quiet evenings after meetings in Côte d'Ivoire. In rooms where investment frameworks, environmental responsibility, regulatory structures, and human livelihoods intersect in ways that are rarely linear or comfortable, the question this thesis addresses remained constant: does this make sense? These contradictions and frictions shaped the work as much as formal literature.

This thesis exists within professional practice. It was written while working with colleagues across sustainability and investment management who continually challenge, refine, and test ideas against implementation reality. In particular, Michael and Johnny, whose conversations, insistence on clarity, and refusal to let anything remain vague or comfortable helped sharpen thinking and continually pushed things toward coherence.

This thesis was written within the rhythms of professional work and motherhood, which did not alternate but coexisted. My son Oliver, now seven, has grown with it, sharing time, space, and attention with a project he could not fully see yet treated seriously. Many women live in this overlap quietly and competently. I stand among them.

I am grateful to my parents for intellectual foundations and for teaching that endurance and thinking are compatible. I am grateful for roots shaped by resilience, non-linearity, and adaptive strength, places where systems self-organize under pressure and where clarity matters because complexity cannot be avoided.

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Abstract

The Sustainable Development Goals (SDGs) have mobilised unprecedented political commitment, yet progress remains uneven. Only 18 percent of targets are currently on track and 18 percent are regressing. This persistent underperformance has shifted attention from goal design to implementation conditions. However, most analytical approaches still struggle to explain why implementation fails, where bottlenecks arise, and how institutional design shapes what can be achieved. Although network-based SDG analyses have improved understanding of interactions across goals and targets, a review of 25 peer-reviewed studies shows that 96 percent focus on formal goal structures while largely omitting the actors, processes, finance conditions, and verification systems through which outcomes are produced and credibly recognised.

This thesis develops an implementation-grounded network framework to address this problem. Drawing on complexity perspectives it introduces the Four-Phase Implementation Network (4PIN), an ontology-based multiplex architecture that represents finance conditionality, organisational capabilities, verification arrangements, value pathways, and SDG attribution in an integrated analytical structure. Verification and recognition are treated as explicit decision points that determine whether implementation efforts translate into verified outcomes, rather than assuming outcomes follow automatically from commitments.

The ontology distinguishes seven relationship types across separate network layers, including finance conditions, implementation dependencies, operational outcomes, business and societal value interpretations, and attribution to SDG targets. Gate-conditioned traversal analysis extends standard reachability methods by capturing how certification approval, evidence requirements, and registry eligibility determine which pathways are feasible under real institutional constraints.

Empirical application to a documented blended finance transaction in the Brazilian biofuel sector. The analysis shows that outcome verification functions as a necessary gate. If verification fails, SDG attribution collapses regardless of prior effort. Certification systems and registry mechanisms shape revenue pathways through channels that are distinct from SDG attribution, clarifying frequent conflation between commercial sustainability narratives and rigorous SDG claims.

For network science, it provides tools for assessing whether network abstractions preserve distinctions that matter for implementation. For sustainable finance, it enables structured testing of covenant and verification design before implementation. For SDG governance, it shifts analytical focus from abstract goal interactions to the institutional conditions under which progress is feasible. The framework supports feasibility assessment, bottleneck diagnosis, and evaluation of institutional design choices, helping align expectations about SDG delivery with what can realistically be achieved.

Keywords: Sustainable Development Goals, implementation pathways, multiplex networks, sustainable finance, complexity, SDG attribution

Resumo

Os Objetivos de Desenvolvimento Sustentável (ODS) mobilizaram um compromisso político sem precedentes, mas o progresso permanece irregular. Apenas 18 por cento das metas encontram-se atualmente no caminho certo e 18 por cento estão em regressão. Este desempenho persistentemente insuficiente deslocou a atenção da conceção de objetivos para as condições de implementação. Contudo, a maioria das abordagens analíticas continua a ter dificuldade em explicar porque é que a implementação falha, onde surgem os estrangulamentos e como o desenho institucional molda aquilo que pode ser alcançado. As análises de rede dos ODS melhoraram a compreensão das interações entre objetivos e metas, mas uma revisão sistemática de 25 estudos revistos por pares demonstra que 96 por cento se centram em estruturas formais de objetivos, omitindo amplamente os atores, processos, condições de financiamento e sistemas de verificação através dos quais os resultados são produzidos e reconhecidos de forma credível.

Esta tese desenvolve um quadro de análise em rede baseado na implementação para abordar este problema. Recorrendo a perspetivas de complexidade e à metodologia de ciência do design, introduz a Rede de Implementação em Quatro Fases (Four-Phase Implementation Network, 4PIN), uma arquitetura multiplex baseada em ontologia que representa a condicionalidade financeira, as capacidades organizacionais, os mecanismos de verificação, as trajetórias de valor e a atribuição aos ODS numa estrutura analítica integrada. A verificação e o reconhecimento são tratados como pontos de decisão explícitos que determinam se os esforços de implementação se traduzem em resultados verificados, em vez de assumir que os resultados decorrem automaticamente dos compromissos assumidos.

A ontologia distingue sete tipos de relações através de camadas de rede separadas, incluindo condições de financiamento, dependências de implementação, resultados operacionais, interpretações de valor empresarial e social, e atribuição a metas dos ODS. A análise de travessia condicionada por portas estende os métodos padrão de alcançabilidade de redes ao captar como a aprovação de certificação, os requisitos de evidência e a elegibilidade de registos determinam quais as trajetórias viáveis sob restrições institucionais reais.

A aplicação empírica a uma transação documentada de financiamento misto no setor dos biocombustíveis brasileiro demonstra a viabilidade analítica. A análise demonstra que a verificação de resultados funciona como uma porta necessária. Se a verificação falhar, a atribuição aos ODS colapsa independentemente do esforço prévio. Os sistemas de certificação e os mecanismos de registo moldam trajetórias de receita através de canais distintos da atribuição aos ODS, clarificando a frequente confusão entre narrativas comerciais de sustentabilidade e reivindicações rigorosas de contribuição para os ODS.

Para a ciência de redes, fornece ferramentas para avaliar se as abstrações de rede preservam as distinções relevantes para a implementação. Para o financiamento sustentável, permite testar de forma estruturada o desenho de cláusulas contratuais e sistemas de verificação antes da implementação. Para a governação dos ODS, desloca o foco analítico das interações abstratas entre objetivos para as condições institucionais sob as quais o progresso é viável. O quadro proposto apoia a avaliação de viabilidade, o diagnóstico de estrangulamentos e a avaliação de escolhas de desenho institucional, ajudando a alinhar as expectativas sobre a concretização dos ODS com aquilo que pode ser realisticamente alcançado.

Palavras-chave: Objetivos de Desenvolvimento Sustentável, trajetórias de implementação, redes multiplex, financiamento sustentável, complexidade, atribuição aos ODS

Contents

Acknowledgements.....	i
Abstract	v
Resumo.....	vii
Contents	v
List of Figures	ix
List of tables.....	xi
List of Acronyms and Abbreviations	xiii
1. Introduction: From SDG Commitment to SDG Implementation	1
1.1 Persistent underperformance of the Sustainable Development Goals	1
1.2 Implementation pathways as complex systems	2
1.3 The role of sustainable finance in shaping implementation.....	3
1.4 Limits of Existing SDG Analytics	5
1.5 Research Objective	6
1.6 Structure of the thesis	7
2. Literature Review and Conceptual Background: SDG Governance, Implementation, and Attribution.....	9
2.1 Introduction and Overview of Conceptual Strands.....	9
2.2 Evolution of Global Goal Frameworks and the SDG Hierarchy	10
2.2.1 From MDGs to SDGs	10
2.2.2 The SDG hierarchical architecture and its analytical implications	11
2.3 Implementation, Attribution, and Governance Architectures.....	12
2.3.1 Implementation science and its application to the SDGs	12
2.3.2 Attribution, contribution, and causality in complex systems	14
2.3.3 Governance architectures for SDG implementation.....	15
2.4 Sustainable Finance, Conditionality, KPIs, and Verification.....	16
2.4.1 Evolution of Sustainable Finance Markets	16
2.4.2 Financial Instrument Typology and Conditionality Mechanisms	17
2.4.3 KPIs, Materiality, and Disclosure Frameworks.....	18
2.4.4 Greenwashing, Market Integrity, and Agency Dynamics	20
2.5 Network and Complexity Foundations, SDG Network Studies, and the Gap.....	21

2.5.1 Foundations of network science and complexity	21
2.5.2 Evolution of SDG network modelling approaches	23
2.5.3 Multilayer and higher-order networks for implementation analysis.....	25
2.5.4 Diagnostic framework, identified gap, and positioning of this thesis.....	27
3. Diagnostic Review of SDG Network Approaches.....	31
3.1 The Challenge of Modeling SDG Interdependencies	31
3.2 Development of the Ontology-Based Network Framework	35
3.3. Evaluation Framework for Network Science Application to SDG studies	38
3.3.1. Identification and Selection of SDG Network Studies.....	39
3.3.2. Coding Procedure and Analytical Approach	39
3.3.3. Phase I: Framing.....	43
3.3.4 Phase II: Abstraction	44
3.3.5. Phase III: Conceptualization.....	45
3.3.6 Phase IV: Analysis.....	47
3.4 Findings.....	49
3.4.1 Results of the Framework Application.....	49
3.4.2 Insights.....	52
3.4.3 Practical Implications	53
3.5 Limitations and Challenges	54
4. An Implementation-Grounded Multiplex Network Framework for SDG Analysis	55
4.1 Design Requirements.....	55
4.1.1 Responding to the Implementation Gap	55
4.1.2 Requirements Derived from Sustainable Finance Practice.....	56
4.1.3 Core Design Principles	59
4.2 Framework Overview.....	59
4.2.1 The SVCP Organising Logic.....	60
4.2.2 The 4PIN Method.....	62
4.2.3 Phase I Framing: system definition and research questions.....	62
4.3. Ontological Questions.....	63
4.3.1 Phase II Abstraction: ontology and modelling grammar.....	63
4.3.2 Core Ontological Classes.....	65
4.3.3 Ontological Relations	69
4.3.4 Ontological Constraints.....	70
4.4 Multiplex Architecture	71

4.4.1 Phase III Conceptualisation: Network Representation	71
4.4.2 Seven-Layer Architecture.....	73
4.4.3 Gate Implementation.....	73
4.5 Analytical Affordances	75
4.5.1 Phase IV Network Model: Instantiation and Analysis	75
4.5.2 Pathway Feasibility Analysis	75
4.5.3 Comparison with Standard SDG Network Approaches.....	76
4.6 Empirical Application of the Implementation-Grounded Multiplex Framework.....	77
4.6.1 Case Context and Documentary Evidence	78
4.6.2 Evidence Handling and Network Instantiation	80
4.6.3 Pathway Analysis and Bottlenecks.....	82
4.6.4 Counterfactual Analysis and Decision Implications	84
5. Conclusion and Future Research	85
5.1 Contribution to Network Science.....	85
5.1.1 Methodological Innovation: Ontology-Driven Network Design.....	85
5.1.2 Architectural Contribution.....	86
5.2 Contribution to Sustainable Finance.....	87
5.2.1 Finance as a System of Constraints.....	87
5.2.2 Addressing Greenwashing Structurally	87
5.3 Contribution to SDG Governance	88
5.3.1 From Interaction Patterns to Implementation Pathways	88
5.3.2 Bridging National Implementation and Finance-Enabled Pathways.....	89
5.4 Limitations, Extensions and Future Research	89
5.4.1 Limitations of the Current Framework	89
5.4.2 Extensions and Future Research Directions.....	90
Bibliography.....	93
 Annex 1.....	 105
Annex 2.....	106
Annex 3.....	107
Annex 4.....	108

List of Figures

Figure 1. The Scientific Method for Network Modelling.....	37
Figure 2. Classification framework for evaluating SDG network studies across four methodological phases and eight analytical steps.).	41
Figure 3. Results of SDG network modelling approaches classification.	50
Figure 4. SVCP with Gates and SDG attribution.....	61
Figure 5. Ontological abstraction of the 4PIN domain (OWL).....	65
Figure 6. FS network graph: finance-gated pathways from covenants through capabilities to outcomes, value interpretations, and SDG targets.	82

List of tables

Table 1. Main strands in SDG network related literature	35
Table 2. Distribution of studies across methodological tiers (A/B/C) for each of the eight analytical steps.	51
Table 3. Ontology-to-network representation mapping.....	72
Table 4. Comparison between standard SDG network approaches and 4PIN	77
Table 5. Document corpus for the FS case	79
Table 6. Node inventory by layer.....	80
Table 7. Minimal cut sets for key SDG targets and revenue nodes.	83

List of Acronyms and Abbreviations

4PIN	Four-Phase Implementation Network
CBD	Convention on Biological Diversity
CBI	Climate Bonds Initiative
CBIO	Decarbonization Credit (Crédito de Descarbonização)
CFIR	Consolidated Framework for Implementation Research
CSR	Corporate Social Responsibility
DESA	Department of Economic and Social Affairs (see also UN DESA)
ESAP	Environmental and Social Action Plan
ESG	Environmental, Social and Governance
EU	European Union
FAO	Food and Agriculture Organization
FS	Fueling Sustainability (case study project)
FSC	Forest Stewardship Council
GHG	Greenhouse Gas
GSS+	Green, Social, Sustainability and Sustainability-Linked bonds
ICSU	International Council for Science
IFC	International Finance Corporation
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
ISO	International Standards Organization
KPI	Key Performance Indicator
MDG	Millennium Development Goal
MRV	Monitoring, Reporting, and Verification
NDPE	No Deforestation, No Peat, No Exploitation
OECD	Organisation for Economic Co-operation and Development

OWL	Web Ontology Language
PRI	Principles for Responsible Investment
SAF	Sustainable Aviation Fuel
SBTi	Science Based Targets initiative
SDG	Sustainable Development Goal
SEN	Social-Ecological Network
SFIR	Sustainable Finance Information Requirement
SLB	Sustainability-Linked Bond
SPV	Special Purpose Vehicle
SVCP	Sustainable Value Creation Plan
UN	United Nations
UN DESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
USD	United States Dollar

Introduction: From SDG Commitment to SDG Implementation

1.1 Persistent underperformance of the Sustainable Development Goals

The Sustainable Development Goals (SDGs), adopted by the United Nations General Assembly in 2015, constitute the most comprehensive global framework ever established to guide social, environmental, and economic development. They articulate 17 goals, operationalised through 169 targets and monitored by 231 global indicators, with the explicit ambition of achieving transformative change by 2030 (UN, 2015). The framework has been widely embraced by governments, international organisations, financial institutions, and private actors as a common reference point for development priorities.

Despite this broad uptake, progress toward the SDGs remains deeply uneven. The most recent global assessment reveals a sobering picture: only 18% of targets are on track to meet the 2030 deadline, with an additional 17% showing moderate progress, meaning that barely one-third of all targets demonstrate adequate advancement. In stark contrast, 48% of targets are progressing insufficiently, including 31% with only marginal gains and 17% showing no measurable progress whatsoever. Most concerning, 18% of targets have actively regressed below their 2015 baseline levels, representing a reversal of developmental gains. These patterns persist across regions and sectors, suggesting that the challenge is not limited to specific policy domains or geographic contexts (UN DESA, 2024, 2025).

This persistent underperformance has increasingly shifted attention away from the design of the SDGs themselves towards the conditions under which they are implemented (Biermann et al., 2017). Goals and indicators provide orientation and a shared language, but they do not generate outcomes. Observable progress depends on the existence of viable implementation pathways that translate commitments into action and action into outcomes that can be recognised and sustained.

Empirical research across multiple SDG domains points to recurring implementation barriers. These include limited institutional capacity, misaligned incentives, fragmented governance, contested land and resource rights, insufficient monitoring, and weak enforcement mechanisms (Nilsson et al., 2016; OECD, 2020). In biodiversity governance, for example, formal commitments to conservation coexist with continued habitat loss due to enforcement gaps, conflicting land-use claims, and failures in monitoring and verification (Brondizio et al., 2019; CBD, 2020; Ferraro & Pressey, 2015). Similar patterns appear in energy transitions, agricultural sustainability, and social inclusion policies (FAO, 2022; Sovacool, 2016; UN STATS, 2023).

Analytical approaches that focus primarily on targets and indicators struggle to account for these dynamics. By abstracting away from the mechanisms through which outcomes are produced and recognised, they risk misdiagnosing both the sources of failure and the levers available for intervention (Biermann et al., 2017; Hickel, 2020). This thesis develops an approach that examines how SDG outcomes are produced. Instead of treating targets and indicators as endpoints, it focuses on the concrete pathways through which outcomes are implemented, verified, and recognised. This makes it possible to ask not only whether progress is occurring, but whether it is feasible under the conditions that shape real-world implementation.

Implementation pathways depend on institutional capacity, resource availability, and external oversight. Biodiversity conservation (SDG 15) illustrates this: countries adopt commitments, donors pledge funds, and indicators are tracked. Yet protected areas remain unenforceable, deforestation regulations go unenforced, and degraded ecosystems stay unrestored because implementation actors lack capacity, verification systems fail, or land tenure conflicts block progress (Turnhout et al., 2020). Analytical approaches that ignore these dynamics misdiagnose problems and propose ill-suited solutions.

1.2 Implementation pathways as complex systems

Implementation of the SDGs can be understood as progressing through implementation pathways: sequences of actions, decisions, capabilities, and verification processes that must align for outcomes to materialise and be recognised. These pathways exhibit the characteristics of complex systems. They involve multiple interacting components, operate across organisational and spatial scales, and unfold over time through interdependent steps. Outcomes emerge from interactions among policies, institutions, actors, and material systems, rather than from linear cause-effect relationships (Holland, 2006; Mitchell, 2009).

Complex systems theory highlights several properties that are directly relevant to SDG implementation. Non-linearity implies that small changes in rules or conditions can produce disproportionately large effects, while substantial efforts may yield limited results if key constraints are not addressed. Path dependence means that early decisions about governance arrangements, capabilities, and standards shape future possibilities, sometimes locking systems into trajectories that are difficult to reverse. These insights from complexity science emphasise that outcomes emerge from interacting feedbacks and adaptive behaviour rather than from simple linear cause–effect relationships (Levin, 1998; Page, 2006) .

Three properties matter for SDG implementation. First, small changes produce disproportionate effects. Adjusting certification requirements can unlock market access for thousands of smallholders; a verification delay can trigger financing withdrawal across multiple domains. Second, path dependencies emerge from feedback loops. Early capability investments enable later outcomes; early verification failures constrain future recognition regardless of later effort. Third, threshold effects mean partial progress often fails. Systems require coordination across multiple actors before outcomes materialise (Folke et al., 2021; Holland, 2006) .

These properties are evident in many SDG-relevant contexts. Renewable energy projects may secure financing and technical capacity but still struggle to deliver expected outcomes when institutional and policy conditions, including regulatory authorisations, institutional uncertainty, and risk-related constraints, delay implementation or undermine investor confidence.(Flammer, 2021; OECD, 2018) . Empirical reviews show that investor decisions in renewable energy depend on policy design features and institutional conditions that shape perceived risk and return (Polzin et al., 2019).

Although agricultural sustainability initiatives may improve practices on the ground they may fail to achieve recognition if monitoring systems cannot produce admissible evidence. In such cases, intent and effort are insufficient; feasibility depends on navigating a structured sequence of conditions such as regulatory authorisations, capability requirements, verification standards, and evidence thresholds (Turnhout et al., 2020).

Analytical tools that assume smooth, continuous progress or rely on aggregate correlations are ill-suited to capture these dynamics. Understanding SDG delivery therefore requires approaches that can represent pathway structure, constraints, and decision points explicitly (Biermann et al., 2017).

1.3 The role of sustainable finance in shaping implementation

Sustainable finance has become a central mechanism through which SDG-related objectives are pursued. Instruments such as green bonds, sustainability-linked loans, and blended finance facilities are designed to mobilise capital toward sustainability priorities and to influence organisational

behaviour. Global issuance of sustainable debt has increased sharply over the past decade, reaching multi-trillion-dollar cumulative volumes and consolidating sustainability within mainstream financial markets (CBI, 2025b).

In operational terms, however, sustainable finance does not function as unconditional support for desired outcomes. It operates through conditionality. Financial agreements specify requirements that must be met for capital to be accessed, retained, or priced favourably. These requirements take the form of covenants, action plans, performance thresholds, eligibility criteria, and clauses that trigger penalties or acceleration in the event of material breaches (Flammer, 2021; Auzepy et al., 2023).

Verification and assurance processes play a central role in this structure. Outcomes are not simply observed; they are validated against defined evidence standards. Certification schemes, audit protocols, and third-party assurance frameworks determine what counts as admissible proof and at what level of confidence (Cohen and Simnett, 2015; O'Dwyer and Unerman, 2020). Failure to meet verification requirements can block recognition regardless of implementation effort.

These conditions structure implementation as they determine organisational priorities, required capabilities, and outcome recognition. Different instruments impose different structures. Green bonds restrict capital to pre-defined projects with verified allocation (Flammer, 2021). Sustainability-linked bonds embed performance targets without earmarking capital, using pricing and disclosure as incentives (Auzepy et al., 2023). Blended finance combines concessional public capital with commercial investment, layering donor safeguards, commercial returns, and certification standards (OECD, 2018).

Verification determines outcome recognition. Standards vary: Climate Bonds Initiative certification for green bonds (CBI, 2025a), Equator Principles for project finance (EQ, 2025), Science Based Targets for climate commitments (SBTi, 2025), ISO standards for environmental management (14001), GHG accounting (14064), and assurance (14065) (ISO, 2025). Each defines admissible evidence such as site audits, remote sensing, system documentation, stakeholder consultations, and assurance levels from limited review to reasonable assurance (Cohen and Simnett, 2015; O'Dwyer and Unerman, 2020).

Verification failure blocks downstream pathways, that is, the subsequent stages through which operational outcomes are translated into SDG attribution, perceived legitimacy, and financial benefits such as pricing advantages or access to new facilities. When verification requirements are not met, these pathways are closed regardless of implementation effort. to attribution, legitimacy, and financial benefit regardless of implementation effort. This creates a distinction between actions taken, outcomes achieved, and outcomes recognised (Flammer, 2021;Auzepy et al., 2023). Research on sustainability-linked instruments and sustainability reporting shows that KPI selection often reflects data availability rather than materiality, leading to verification of measurable activities rather than transformational outcomes (Du Toit, 2024; Boiral, 2013) On the other hand, greenwashing risks emerge when standards permit selective disclosure or lack independent assurance (Flammer and Bansal, 2017; Auzepy et al., 2023). Additionally, analytical tools for examining how finance conditions and verification requirements shape implementation pathways remain limited (Casasnovas et al., 2025;Auzepy et al., 2023).

This distinction matters operationally: organisations can act, deliver change, and still fail to have outcomes recognised. In finance-enabled SDG delivery, recognition is often the decisive step that determines legitimacy, disclosure, and access to continued financing. Treating finance and verification as background context rather than structural elements obscures how implementation pathways actually function.

1.4 Limits of Existing SDG Analytics

Network science forms one of the core analytical pillars of complexity science. It provides a powerful way to study systems in which outcomes emerge from interconnected elements rather than isolated components, making it especially relevant for analysing the structured interdependencies among SDG goals, targets, and implementation conditions. Network approaches to SDG analysis have advanced understanding of goal interdependencies (Le Blanc, 2015;Nilsson et al., 2016;Pradhan et al., 2017). However, a systematic review of 25 peer-reviewed SDG network studies reveals persistent limitations (Pasishnyk & Lopes, 2025).

Most models focus on goal, target, or indicator interactions through correlations, expert judgments, or conceptual mappings without representing implementation mechanisms. Two paradigms dominate. Semantic approaches (11/25 studies) derive connections from text co-occurrence or expert elicitation. These map discourse but conflate semantic proximity with causal mechanisms. Statistical approaches (12/25) infer relationships from correlation, Granger causality, or spatial econometrics. These identify co-variation but cannot distinguish correlation from causation or reveal underlying mechanisms (Pasishnyk & Lopes, 2026).

Most critically, 24 of 25 studies (96%) model only formal SDG structures (goals, targets, indicators) without including actors, processes, or mechanisms. No study represents government agencies, financial institutions, certification bodies, or community organisations as nodes. None models finance conditions, verification processes, or institutional arrangements as edges. This limits analyses to describing goal relationships without addressing whether outcomes are achievable under real constraints or where bottlenecks emerge (Pasishnyk & Lopes, 2025).

Architectural simplicity compounds this. Twenty-three of 25 studies use monoplex structures (one node type, one edge type). Only two explore multilayer designs. None use hypergraphs despite multi-actor coordination requirements in SDG implementation. This is striking given that sustainability transformations involve multiple entity types (actors, policies, ecosystems, technologies) connected through diverse relationships (funding, regulation, ecological flows, knowledge exchange) across scales (Pasishnyk & Lopes, 2025).

These models describe goal relationships but cannot address feasibility, sequencing, or constraint interaction central to implementation (Horvath et al., 2022).

1.5 Research Objective

This thesis develops an implementation-grounded network framework for analysing how conditional finance shapes feasible pathways to verifiable SDG outcomes.

The framework integrates finance, implementation, verification, and SDG attribution within one analytical structure. Distinct relation types preserve conceptual separation between finance conditions, organisational capabilities, operational outcomes, and SDG attribution. Verification and recognition are treated as binding decision points rather than assumed outcomes.

The contribution is methodological focusing on feasibility: which outcomes are reachable under documented conditions, where bottlenecks arise, how alternative configurations affect pathway viability. This differs from impact evaluation (quantifying causal effects) and predictive modeling (forecasting indicator values). The framework supports pathway analysis: mapping which implementation sequences can traverse finance conditions, capability requirements, verification gates, and recognition decisions to reach outcomes eligible for SDG attribution.

The approach follows design science methodology (Hevner et al., 2004): knowledge creation through building and evaluating purposeful artifacts. The artifact here is an analytical framework - a structured ontology operationalised as a multiplex network, designed to address the gap between existing SDG analytics and implementation realities. Evaluation occurs through demonstration, not statistical generalisation.

This justifies key choices. First, the framework is theory-driven, not data-driven. The ontology derives from understanding how conditional finance, implementation capabilities, and verification systems function, not from statistical patterns. Second, empirical application prioritises detailed case-based tracing over breadth. A well-documented finance transaction can demonstrate feasibility and reveal dynamics aggregated data would obscure. Third, validity comes from transparency of choices, traceability of evidence, and coherence between structure and instantiation, not sample representativeness or prediction accuracy.

The complexity perspective (Meadows and Wright, 2008; Holland, 2006) shapes the analytical approach by emphasising non-linear dynamics, feedback loops, and threshold effects. Here, network representations must capture structural dependencies: how capability investments enable outcomes, how verification decisions gate recognition, how finance conditions constrain sequences. The multiplex architecture responds to this by organising distinct relationship types, such as conditionality, implementation dependency, verification, attribution, as separate layers representing pathway structure. On this basis, the framework treats implementation systems as integrated structures rather than fragmented analytical domains.

To address this objective, the thesis is guided by three research questions:

1. How do existing SDG network models limit the analysis of implementation pathways and feasibility in finance-enabled contexts?
2. How can a network-based framework be designed to represent finance conditions, implementation dependencies, verification processes, and SDG attribution within a coherent analytical model?
3. What new insights emerge when SDG outcomes are analysed as constraint-driven implementation pathways rather than as abstract interactions or indicator correlations?

These questions structure the cumulative argument developed across the thesis.

1.6 Structure of the thesis

The thesis is organised into five chapters that build a cumulative argument from conceptual diagnosis to methodological development and empirical demonstration.

Chapter 1 establishes the problem context. It examines the persistent underperformance of the Sustainable Development Goals and argues that the challenge lies not primarily in the goals themselves, but in the conditions under which implementation occurs. The chapter introduces implementation pathways as complex systems, explains the structuring role of sustainable finance and verification, identifies the limitations of existing SDG analytics, and formulates the research objective and guiding questions.

Chapter 2 develops the conceptual background. It reviews the evolution of global goal frameworks and the hierarchical structure of the SDGs, discusses implementation science and attribution challenges, and analyses governance architectures relevant to SDG delivery. It then examines sustainable finance as a conditional implementation architecture, before turning to network science and complexity theory. The chapter concludes by identifying the gap that motivates an implementation-grounded network approach.

Chapter 3 presents a diagnostic review of existing SDG network studies. It applies an ontology-based evaluation framework to a corpus of peer-reviewed work in order to assess how SDG network science currently represents systems, what becomes analytically visible as a result, and what is systematically excluded. The findings demonstrate that most studies model only formal SDG structures and rarely represent implementation actors, finance conditions, verification mechanisms, or institutional processes, reinforcing the methodological gap this thesis addresses.

Chapter 4 develops the implementation-grounded network framework. It specifies the design requirements derived from the diagnostic review and from sustainable finance practice, introduces the organising logic, and defines the ontology that distinguishes finance conditionality, implementation capabilities, operational outcomes, verification and recognition, and SDG attribution. The chapter then presents the multiplex network architecture and analytical capabilities of the framework, showing how it supports feasibility-oriented pathway analysis.

Chapter 5 concludes the thesis. It synthesises the methodological contributions to network science, sustainable finance, and SDG governance, highlighting how the framework shifts analysis from abstract interaction mapping toward constraint-driven feasibility assessment. The chapter also reflects on limitations, outlines potential extensions, and identifies directions for future research.

Literature Review and Conceptual Background: SDG Governance, Implementation, and Attribution

2.1 Introduction and Overview of Conceptual Strands

This chapter sets the conceptual background for the thesis and reviews the literature that informs an implementation-grounded approach to SDG analysis. Three bodies of work are central.

First, research on SDG governance and implementation examines how global commitments translate into operational change, and why this translation often fails. A recurring theme is that the SDG framework's hierarchy of goals, targets, and indicators supports monitoring and comparability, but offers limited guidance on how outcomes are actually produced. Implementation pathways remain underspecified, and attribution is difficult because SDG-relevant change unfolds through multi-actor, multi-sector processes that vary by context.

Second, the sustainable finance literature shows that mobilising capital for sustainability objectives typically relies on conditionality. Covenants, performance thresholds, eligibility criteria, and verification requirements shape what organisations prioritise and what can be recognised as credible performance. Finance therefore does not only enable action, it also structures action through requirements and evidence standards.

Third, network science has been applied widely in sustainability research as a way to represent interdependence in complex systems. Within the SDG domain, network models have contributed valuable insight into patterns of interaction among goals, targets, and indicators. At the same time, much of this work remains oriented toward mapping relationships within the SDG framework itself rather than modelling the implementation systems that generate outcomes, including institutional arrangements, finance conditions, and verification processes.

The next sections review SDG evolution, implementation science, governance structures, and sustainable finance conditions. Section 2.2 reviews the evolution of global goal-setting and the SDG hierarchical architecture. Section 2.3 introduces implementation science, attribution, and governance architectures. Section 2.4 turns to sustainable finance as a conditional implementation architecture. Section 2.5 develops the network and complexity foundations, the diagnostic evidence on SDG network studies, and the specific gap this thesis addresses.

2.2 Evolution of Global Goal Frameworks and the SDG Hierarchy

2.2.1 From MDGs to SDGs

The Sustainable Development Goals emerged from a longer trajectory of global development goal-setting. Reviewing this evolution clarifies why SDG implementation differs in kind from earlier agendas, and why analytical tools designed for linear intervention settings often perform poorly in SDG contexts.

The Millennium Development Goals (2000-2015) established a widely influential template for global target-setting: eight goals, 21 targets, and 60 indicators, strongly focused on poverty reduction and basic social outcomes in low- and middle-income countries (Hulme, 2009). The MDGs were frequently characterised as technocratic and top-down, developed largely through UN agencies and development institutions, with relatively limited participatory input (Fukuda-Parr & Hulme, 2011). This process privileged measurability and tractable targets.

In many domains, the MDGs also aligned with intervention logics for which causal pathways were comparatively well established. Public health goals provide a clear example, notably, for MDG 4 on child mortality, a set of known interventions, such as immunisation, oral rehydration therapy, and skilled birth attendance, could be scaled through health systems and donor-supported programmes (Waage et al., 2010). This facilitated relatively direct narratives linking commitments to interventions and to measured outcomes.

At the same time, the MDG framework drew substantial criticism. Easterly (2009) argued that global targets often failed to respect local context and national ownership. (Saith, 2006) noted that aggregate targets could mask distributional failures, where national averages improve while marginalised groups see limited gains. Vandermoortele (2011) emphasised that the MDGs underweighted environmental sustainability, institutional development, and structural economic transformation, thereby risking short-term improvement without durable change.

The SDGs were shaped explicitly by these critiques. The post-2012 process, influenced by Rio+20, moved toward a more open, politically negotiated framework with extensive stakeholder consultation across governments, civil society, the private sector, and scientific communities (Kamau et al., 2018). The result was a universal agenda, designed to apply across income contexts, and explicitly integrating environmental, social, and economic dimensions within a single framework.

This shift has major analytical consequences. Notably, the SDGs incorporate goals with very different degrees of specificity and tractability. Some goals express broad normative aspirations, such as SDG 16 on peace, justice, and institutions. Others are sectoral and operationally familiar, such as SDG 2 on hunger. Still others cut across domains, such as SDG 13 on climate action. The framework's comprehensiveness albeit reflecting political inclusion also increases coordination and implementation difficulty.

Fukuda-Parr & McNeill (2019) document how tensions between scientific aspirations for integration and the realities of political negotiation produced a framework that is simultaneously comprehensive and fragmented. Scientific assessments also highlighted structural issues. The International Council for Science (ICSU, 2015) identified internal inconsistencies and measurement limitations, including targets lacking measurable indicators, indicators capturing policy existence rather than substantive outcomes, and goal-level aggregation that obscures sub-national variation and cross-sectoral linkages relevant to implementation.

The overall implication is that many SDG targets require systemic transformation rather than discrete intervention scaling. SDG 7 on clean energy, for instance, often requires policy reform, market design, grid investment, and institutional restructuring, not only project finance. SDG 12 on responsible consumption and production implicates manufacturing systems, waste and materials governance, consumer behaviour, and global value chains. In such cases, causal pathways are not settled and are highly context-dependent (UN, 2019). This creates implementation problems that cannot be reduced to monitoring progress against indicators alone.

2.2.2 The SDG hierarchical architecture and its analytical implications

The SDGs are structured hierarchically. Goals articulate broad objectives, targets specify domains of change, and indicators provide measurement proxies. In practice, this hierarchy is often operationalised through dashboards and composite indices, which can create the impression that SDG progress is primarily a measurement exercise.

Analytically, the hierarchy matters because each level plays a different role. Goals are normative endpoints. Targets operationalise desired change in specific domains. Indicators are measurement devices, often imperfect, designed to approximate underlying states. Treating these levels as interchangeable creates persistent confusion between measurement and achievement.

Indicators do not capture “outcomes” in a straightforward way. Indicator movement may reflect methodological revisions, data quality changes, or shifts in reporting capacity. It may also represent partial change, where one measurable dimension improves while other dimensions remain stagnant. Maternal mortality ratio (indicator 3.1.1), for instance, captures one critical health outcome, but cannot capture other dimensions of reproductive health system performance, including quality of care, access equity, or respectful treatment, which condition whether improvements are robust or sustained.

Measurement critiques highlight this problem. Hickel (2020) (Hickel, 2020) argues that many indicators use thresholds and aggregates that hide distributional dynamics. Extreme poverty measures, for example, may show improvement even where relative poverty, vulnerability, or inequality persist. Education indicators can reflect enrolment rather than learning outcomes. Environmental indicators can reflect formal protection rather than effective ecological condition. The issue is not that indicators are useless, but that indicator improvement can be misread as systemic transformation.

UN statistical documentation and SDG progress reports, for example, (UN, 2019; Biggeri et al., 2019) show how indicator selection was constrained by data availability and institutional feasibility. Many indicators required methodological development or lacked reliable data when adopted, creating uneven measurement quality across targets. This introduces a structural mismatch: targets often describe systemic changes, while indicators may capture only fragments of those transformations.

The ICSU (2015) review also highlights inconsistencies within the hierarchy. Some targets specify substantive outcomes, while others specify policy means, mixing ends and means at the same level. Some indicators measure direct outcomes, while others measure proxies such as policy existence. At the goal level, overlapping causal drivers and dependencies exist, but institutional arrangements frequently treat goals as discrete portfolios.

These features point to the need for a clear analytical separation between commitments (adoption of goals and targets), actions (implementation efforts), outcomes (operational states that can be evidenced), and attribution (credible linkage between interventions and outcomes). When these distinctions are blurred, it becomes difficult to explain why progress stalls even when activity appears substantial.

2.3 Implementation, Attribution, and Governance Architectures

2.3.1 Implementation science and its application to the SDGs

Implementation science emerged from observations that interventions with strong evidence bases often fail to achieve intended outcomes when deployed in real-world settings. The field studies how policies, programmes, and practices are adopted, adapted, embedded, scaled, and sustained in specific organisational and institutional context (Nilsen, 2015). Though rooted in health services research, its concepts are increasingly used to interpret sustainability and development programmes, where implementation failure is a recurrent challenge.

Fixsen et al. (2005) identify four core components that distinguish successful from unsuccessful implementation: competent practitioners, organisational supports (administration, decision support, and systems alignment), leadership engagement, and a supportive external environment. The key implication is that failure often reflects missing implementation conditions rather than flawed intervention design.

May (2013) Normalization Process Theory offers a complementary lens, focusing on how practices become routinely embedded in organisational life. It identifies four mechanisms: coherence (shared understanding of what the practice is), cognitive participation (commitment), collective action (capability and enactment), and reflexive monitoring (feedback and adaptation). A practice may fail to become embedded in organisational routines even when its value is recognised, if operational capacity or feedback mechanisms are weak.

Nilsen (2015) taxonomy distinguishes process models, determinant frameworks, and evaluation frameworks. This matters for SDG implementation because different analytic questions require different tools. Process models specify stages and sequencing. Determinant frameworks diagnose barriers and enabling factors. Evaluation frameworks guide assessment of fidelity, adaptation, and sustainability over time.

Implementation science explains the recurring gap between policy intent and operational outcomes. SDG 6 on water and sanitation illustrates this point. Achieving universal access to safe drinking water requires far more than infrastructure investment. It also requires organisational competence, operation and maintenance systems, financing and tariff structures, regulatory oversight, and coordination with public health and education. Progress can stall if any component is weak, even when others are in place.

Implementation science also clarifies why general solutions often fail when transferred across contexts. The Consolidated Framework for Implementation Research (Damschroder et al., 2009) distinguishes five domains that shape outcomes: intervention characteristics, the external environment, organisational conditions, individual characteristics, and implementation processes. An intervention may be technically effective yet fail in settings where enabling conditions differ, including supply chain constraints, weak maintenance capacity, misaligned incentives, or limited local legitimacy.

The SDG framework itself largely avoids specifying implementation pathways. Targets describe desired outcomes without detailing the conditions and sequences required to achieve them. This creates an implementation gap: the missing link between what is monitored and what must be built, managed, and sustained in practice. Analytical approaches that focus on goal-level interaction without representing implementation mechanisms are limited in diagnosing where and why this gap emerges.

2.3.2 Attribution, contribution, and causality in complex systems

Attribution is a central challenge in SDG governance. SDG outcomes emerge from multi-actor systems in which policies overlap, causal chains are long, and effects unfold over extended time periods. Establishing whether observed change can be attributed to specific interventions is often difficult, yet attribution claims underpin accountability, learning, and resource allocation.

Evaluators distinguish between attribution and contribution. Attribution claims seek to establish that outcomes would not have occurred without a particular intervention, a counterfactual standard often associated with experimental or quasi-experimental designs (White, 2009). Such approaches can be valuable for discrete interventions, but they encounter limitations in many SDG contexts. Interventions adapt over time, systems change in parallel, control groups are often infeasible, and outcomes may not be measurable within typical evaluation timeframes.

Contribution analysis offers a more appropriate standard for complex systems, aiming to establish a credible causal narrative without claiming exclusivity (Mayne, 2001). It builds a contribution story linking actions to outcomes through plausible mechanisms and evidence. Theory-based evaluation similarly emphasises explicit causal assumptions and mechanisms through theories of change, enabling assessment of whether expected pathways operated in practice (Chen, 2015).

Process tracing strengthens this approach by focusing on causal mechanisms through sequences of events and evidence tests, rather than relying exclusively on aggregate outcome correlations (Befani & Stedman-Bryce, 2017) demonstrate how Bayesian logic can be used to update causal confidence as evidence accumulates, which is particularly suitable for long causal chains and mixed evidence bases.

SDG attribution presents specific difficulties. First, many outcomes are co-produced across sectors. Food security improvements can arise from agricultural policy, social protection, health interventions, and trade dynamics, often interacting. Second, temporal lags decouple interventions from observable outcomes. Education investments may take years to translate into labour market and poverty effects. Climate and biodiversity outcomes often unfold over decades. Third, transboundary and global commons dynamics complicate national attribution, because actions in one jurisdiction affect outcomes elsewhere (Messerli et al., 2019)

For the purposes of this thesis, an outcome is treated as an operational state that can be evidenced and verified under defined standards. Indicators may proxy these states but cannot replace them. Credible claims about SDG contribution therefore require explicit implementation pathways, not only indicator movement.

2.3.3 Governance architectures for SDG implementation

SDG implementation depends on governance architectures that allocate responsibilities, coordinate across sectors and levels, and establish accountability. Unlike narrower sector programmes, the SDGs require cross-ministerial coordination and multi-level engagement, because many targets cut across policy domains and are implemented through overlapping institutions.

Polycentric governance theory provides a useful frame for understanding how complex problems can be addressed through multiple, overlapping decision centres rather than a single authority. Polycentricity can enable experimentation and local adaptation, which is relevant to SDG implementation across diverse contexts. At the same time, polycentric systems can fragment responsibilities unless coordination mechanisms exist.

Multi-level governance research similarly distinguishes between general-purpose jurisdictions and task-specific authorities, highlighting how overlapping mandates can create coordination challenges. SDG governance often resembles a task-specific, overlapping system: environment ministries, finance ministries, energy regulators, land agencies, and local governments each hold partial responsibilities. Without explicit coordination, policies that advance one target can undermine another.

Accountability structures further shape implementation. (Bovens, 2007) distinguishes vertical accountability (hierarchical reporting), horizontal accountability (institutional checks and peer oversight), and diagonal accountability (citizens and stakeholders). SDG governance uses all three, but enforcement is uneven. Voluntary National Reviews depend largely on self-reporting. Parliamentary and audit oversight vary in capacity. Civil society monitoring depends on transparency and access to reliable data.

Institutional arrangements for SDG coordination differ by country. Some states establish dedicated coordination bodies, while others mainstream SDG responsibilities into planning and budgeting processes. Each approach has trade-offs. Dedicated bodies can provide focus and visibility but risk marginalisation if not connected to core fiscal and policy institutions. Mainstreaming can integrate SDGs into existing processes but may dilute responsibility and weaken follow-through.

Scale matters as well. Many SDG-relevant services are implemented locally, while enabling policy and finance are often national. Capacity constraints at subnational levels can therefore block progress even where national commitments and funding exist. These governance realities reinforce a central point: SDG outcomes depend on the structure of implementation systems, not only on the declaration of goals or the presence of indicators.

2.4 Sustainable Finance, Conditionality, KPIs, and Verification

2.4.1 Evolution of Sustainable Finance Markets

Sustainable finance, understood as the incorporation of environmental, social, and governance considerations into financial decision-making, has moved from a values-led niche to a large, institutionally structured market. This historical shift matters because it explains why finance increasingly operates as a mechanism that shapes what firms must build and demonstrate, not only as a source of funding (Zerbib, 2019).

Early waves of sustainable finance are typically traced to socially responsible investing in the 1970s and 1980s, where the main practice was exclusionary screening of sectors such as tobacco, weapons, or gambling. The emphasis was ethical alignment and reputational distance rather than operational change inside firms or measurable environmental outcomes (Renneboog et al., 2008). During this period, the “sustainability” content of finance was mainly expressed in portfolio composition.

From the 1990s onward, sustainability debates broadened, including the spread of “triple bottom line” thinking (Elkington, 1994, 1997) and the emergence of early environmental finance instruments. A pivotal institutional development was the launch of labelled bond markets, especially green bonds, where proceeds are earmarked for eligible projects and reporting and review practices are expected (Cortellini and Panetta, 2021; MacAskill et al., 2021; Zerbib, 2019). The World Bank’s early green bond issuance is widely treated as a landmark moment because it facilitated establishment of the “use of proceeds” logic and accelerated the formation of standards, second-party opinions, and verification practices around allocation and reporting (CBI, 2022; MacAskill et al., 2021).

Growth accelerated sharply after 2015, as global commitments such as the Paris Agreement, and the SDGs themselves, sharpened the scale of investment requirements and intensified policy attention (MacAskill et al., 2021). Market infrastructure expanded in parallel, with taxonomies, disclosure frameworks, verification practices, and data providers supporting rapid product growth (CBI, 2022). By the early 2020s, green, social, sustainability, and sustainability-linked instruments (often grouped as GSS+) were being issued at very large scale, with annual aligned volumes approaching the trillion-dollar range in some years according to Climate Bonds’ tracking (CBI, 2024).

Mainstreaming has also been institutional. Major asset managers, pension funds, and banks incorporated sustainability factors into product design, risk analysis, and engagement strategies. Central banks and regulators increasingly treated climate and nature as financial risk topics, encouraging stress testing, governance expectations, and disclosure norms. In the EU, the Corporate Sustainability Reporting Directive introduced a phased regime for expanded sustainability reporting and assurance, while the surrounding policy environment continues to evolve through political debate about scope and timelines (EC, 2025).

This expansion came with credibility problems. “Sustainable” is not a single, stable category across jurisdictions or standards, and taxonomy fragmentation creates room for inconsistent claims and selective interpretation. The result is a market that is simultaneously larger, more formalised, and more contested.

2.4.2 Financial Instrument Typology and Conditionality Mechanisms

Different sustainable finance instruments embed different logics of conditionality. This is central to the thesis’s perspective: finance is not simply capital moving toward sustainability goals, it is a contract structure that can constrain behaviour, require capability-building, and determine which outcomes become recognisable and valuable.

Green bonds are the clearest example of constraint by design. Their defining feature is the use-of-proceeds restriction: capital must be allocated to eligible activities, and issuers are expected to report on allocation and, often, impacts, typically with some external review. Empirical work suggests that green bond issuance can be associated with improved environmental performance, with mechanisms plausibly linked to monitoring, reputational incentives, and investor scrutiny (Flammer, 2021).

Sustainability-linked bonds (SLBs) and **sustainability-linked loans (SLLs)** shift the constraint architecture away from earmarking and toward performance-based conditions. Capital is not restricted to predefined projects, but pricing changes (step-ups or step-downs) are linked to KPI targets. Research on SLBs has highlighted recurring weaknesses in target ambition, KPI materiality, and the size of financial incentives, which can turn conditionality into low-cost signalling rather than a driver of implementation change (Auzepy et al., 2023). In loan markets, the Sustainability-Linked Loan Principles provide a widely referenced structuring framework, explicitly separating KPI selection, target calibration, and reporting and verification expectations (SLLP, 2025).

Social bonds and **sustainability bonds** apply the labelled, use-of-proceeds logic to social or mixed objectives. They require definitions of eligible activities and beneficiary populations, plus reporting, but the verification and measurement difficulties are often more acute for social outcomes than for many environmental metrics, because causal chains are longer and context sensitivity is higher (Banga, 2019).

Blended finance introduces layered conditionality. It combines concessional or catalytic capital with commercial capital to de-risk transactions and mobilise private investment. Blended structures may include first-loss capital, guarantees, subordinated debt, technical assistance, or political risk insurance, each addressing specific barriers to private capital while introducing donor and safeguard requirements alongside commercial risk-return constraints (OECD, 2018). The &Green Fund, examined in later chapters of this thesis, is an example of such a blended structure, combining concessional capital with commercial co-lenders under safeguard, covenant, and verification requirements designed to mobilise private investment into land-use and agricultural transitions.

Across these instruments, conditionality often operationalises through covenants and related contractual mechanisms. Affirmative covenants can require the establishment of management systems, certifications, traceability systems, grievance mechanisms, or due diligence processes. Negative covenants prohibit certain practices, such as deforestation-linked sourcing or operations in protected areas. Performance-linked conditions tie financial terms to measurable thresholds over time. Material sustainability-related clauses create discontinuities by giving capital providers rights to reprice, renegotiate, or accelerate repayment after specified incidents.

The practical implication is that implementation is shaped by what contracts require firms to build, to document, and to prove, and by what counts as breach or compliance. Conditionality becomes implementation architecture.

2.4.3 KPIs, Materiality, and Disclosure Frameworks

KPIs determine what becomes visible, governable, and tradable as “sustainability performance.” That makes KPI design a choice about implementation priorities, not simply a technical reporting issue.

Materiality frameworks seek to stabilise KPI choice by defining what “matters” in sector-specific and investor-relevant ways. The field is characterised by pluralism: some standards emphasise investor-oriented financial materiality, while others emphasise broader stakeholder and impact materiality. Climate disclosure has been among the most standardised domains, notably through the Task Force on Climate-related Financial Disclosures (TCFD, 2025), and more recently through consolidation efforts under international standard-setting. Nature disclosure frameworks are developing in parallel, with the Taskforce on Nature-related Financial Disclosures (TNFD, 2025) explicitly extending risk and dependency logics beyond climate.

Despite this infrastructure, KPI selection in practice often follows data availability rather than materiality. In sustainability-linked instruments, KPIs frequently concentrate on metrics that are easy to measure and assure (for example, scope 1 and 2 emissions), while excluding value-chain metrics (scope 3), biodiversity outcomes, or more complex social outcomes. Empirical evidence in the SLB space shows that target ambition and incentive strength can be weak, reducing the extent to which KPIs function as binding constraints on behaviour (Auzepy et al., 2023).

This measurability bias matters because it can create an implementation trap: organisations optimise for what can be reported and verified, even when this is not where the most material impacts sit. It also complicates SDG alignment claims. Mapping financial activities to SDG targets requires assumptions about causality, additionality, and contribution, yet these assumptions are rarely made explicit in disclosure practice. This produces a reporting environment with abundant information, but not always information that supports credible pathway reasoning about how finance-enabled change leads to verifiable outcomes.

Monitoring, Reporting, and Verification (MRV) systems define which claims are accepted as credible. In other words, they do not merely observe reality, they shape what becomes eligible as an “outcome” within financial and governance systems.

The “audit society” perspective is useful here: verification practices expand in response to accountability demands, but they also create performative pressures, standardise what counts as evidence, and adjust organisational attention around what is auditable (M. Power, 1999). Verification also has a second-order character: institutions do not only verify outcomes, they specify how verification itself must be conducted, by whom, and with what independence and competence expectations (M. K. Power, 2003).

In sustainable finance, multiple verification architectures operate simultaneously:

- **Green and sustainability bond markets** often rely on external reviews and second-party opinions, and in some cases certification regimes with pre- and post-issuance checks. Climate Bonds’ approach is a prominent example of a market actor building eligibility criteria and verification expectations as part of an integrity ecosystem (CBI, 2025b).
- **Project finance** verification norms are strongly influenced by the Equator Principles, which benchmark to International Finance Corporation Performance Standards (IFC PS) and scale requirements by risk categorisation. The Equator Principles system has broad adoption among project finance institutions and operates as a de facto global baseline for many transactions (EP 2025).
- **Science-based climate commitments** such as SBTi validate target-setting methodologies, while progress measurement and assurance typically rely on additional reporting and assurance infrastructures (SBTi, 2025).

Standards and accreditation regimes shape what evidence is admissible and how costly it is to produce. ISO standards are widely used examples: some focus on management system requirements, others on accounting and verification processes. Assurance also varies in level. Limited assurance provides a lower confidence threshold than reasonable assurance and can be cheaper, but it may detect fewer issues; reasonable assurance is more demanding, increasing confidence but also raising cost barriers, especially for smaller implementers (Cohen & Simnett, 2015).

For implementation analysis, the structural point is simple: outcomes can exist operationally but remain unrecognised until verified, and verification failure can block downstream recognition regardless of effort. MRV therefore acts as a gate that shapes pathway feasibility.

2.4.4 Greenwashing, Market Integrity, and Agency Dynamics

The rapid growth of sustainable finance has increased incentives for sustainability signalling, and therefore increased attention to greenwashing risks and market integrity.

A useful analytical lens is the distinction between substantive and symbolic commitments. Work on long-term orientation suggests that firms and investors with longer time horizons can be more likely to make deeper, value-creating sustainability investments, while short-term incentives may favour signalling with limited operational change (Flammer & Bansal, 2017).

Agency dynamics also matter. Sustainable finance relationships involve information asymmetry between capital providers and recipients: lenders and investors cannot directly observe internal practices, supply chain realities, or the quality of controls. Conditionality, KPIs, and verification can be interpreted as contractual and institutional devices intended to reduce moral hazard and adverse selection problems. In retail and responsible investment contexts, empirical work has examined how investors interpret sustainability information and how trust, product design, and information structure affect decisions (Diouf et al., 2016).

However, conditionality can fail if it is weakly designed or weakly enforced. Evidence from sustainability-linked bond markets highlights recurring issues: unambitious targets, narrow KPIs, limited penalties, and inconsistent assurance expectations (Auzepy et al., 2023). When verification becomes procedural rather than substantive, it can produce compliance theatre rather than transformation.

Policy and market responses are evolving, including stronger disclosure and assurance regimes and efforts to standardise definitions. In the EU, the reporting framework has been implemented with phased requirements, while political negotiations and proposals continue to reshape the scope and timing of obligations (EC, 2025).

From the perspective of this thesis, these integrity dynamics reinforce the need to treat finance conditions and verification structures as part of the implementation system. They shape what is pursued, what is evidenced, and what becomes legible as a contribution to SDG outcomes.

2.5 Network and Complexity Foundations, SDG Network Studies, and the Gap

2.5.1 Foundations of network science and complexity

Network science offers a way to study systems where the important features are not only the components themselves, but also how those components are connected or interact. It does this by representing a system as a graph, with nodes (or vertices) standing for entities in the system and links (or edges) standing for relations between them. This is a deliberately simple formalism, and that is part of its strength. It lets very different domains, from social organisation to infrastructure to ecosystems, be analysed with a shared set of tools.

For sustainability problems, the main promise of network representations is that they make interdependence explicit. Many sustainability outcomes arise from connected processes and institutions rather than isolated interventions. A network model can show which components are tightly coupled, where bottlenecks may form, and how changes may propagate through a system, but only if the model's elements are defined in a way that matches the domain.

Brandes et al. (Brandes et al., 2013) frame network science as operating in two registers at once. The first is theoretical: network science provides concepts that explain relational phenomena even when the exact data are incomplete. The second is empirical and methodological: networks are built from data and then analysed using measures and algorithms. However, most SDG network studies tend to operate predominantly in the empirical register, emphasising measurable interactions and computational techniques while engaging less explicitly with the theoretical grounding of what the network is intended to represent. The practical implication for SDG applications is that any network model is only as meaningful as its translation from a real world system into nodes and edges. Domain knowledge is needed to decide what a node represents (a target, an indicator, an organisation, a capability), what a relation means (co-occurrence, statistical association, dependency, contractual obligation), and what the model is allowed to claim.

Classical graph theory established that relational structure can be analysed mathematically. Euler's solution to the Seven Bridges of Königsberg problem showed that connectivity patterns can be studied independently of geometry (Newman, 2010). Later, random graph theory provided baseline expectations for what network structure looks like in the absence of organising mechanisms. Erdős and Rényi models are useful precisely because they are unrealistic, they provide a neutral reference point from which patterns in observed networks can be interpreted (Bollobás, 2001; Newman, 2010).

Empirical networks in many domains show structures that differ strongly from random graphs. In numerous settings, degree distributions are heavy-tailed, meaning that most nodes have few links while a small number of nodes have very many. Small-world structure has also been widely observed, where clustering remains high while path lengths stay short even as systems grow (Watts & Strogatz, 1998). Scale-free patterns associated with preferential attachment further highlight how connectivity can concentrate around influential hubs (Barabási, 2013; Barabási & Albert, 1999). These features matter because they shape robustness, diffusion, and coordination.

Barabási's synthesis of complex network research emphasises how hubs can arise through cumulative advantage mechanisms such as preferential attachment, where new nodes tend to connect to already well-connected nodes (Barabási, 2013). It is helpful to treat "scale-free" as a pattern that appears in many real systems rather than a universal law, but the broader point remains relevant: concentrated connectivity can make systems resilient to random failures and fragile under targeted disruptions. In policy and implementation contexts, this translates into the possibility that a small number of components, institutions, or processes can disproportionately shape system-wide performance.

Newman (2010) surveys the core analytical toolkit: structural measures such as degree and clustering, centrality measures such as betweenness and eigenvector centrality, community detection, and dynamical processes such as percolation and epidemic spreading. These tools can identify structurally influential nodes and relationships that are not obvious from attributes alone. For SDG-related systems, however, the key question is always representational: centrality is only meaningful if the network has been constructed so that edges correspond to the kinds of interdependencies that plausibly transmit influence or constraint.

This representational issue is particularly important in sustainability contexts because the relevant relations are often heterogeneous. Food systems connect production, logistics, markets, diets, waste, and land use through material flows, information flows, financial relations, and governance rules. Environmental outcomes are shaped by both biophysical processes and institutional arrangements. That is, network models, their graph instantiations, and subsequent analyses must be grounded in domain-specific theory and ontological clarity, rather than relying solely on abstract structural formalisms.

Complexity science focuses on systems whose behaviour cannot be understood by adding up the behaviour of individual parts. Complex systems exhibit non-linear dynamics, emergent properties, adaptation, feedback loops, and path dependence. SDG implementation systems exhibit these features because outcomes depend on interacting actors, evolving institutional settings, and sequences of actions that can be blocked by binding constraints.

Holland (2006) describes complex adaptive systems as systems of interacting agents whose simple local rules can produce emergent system-level patterns. Agents adapt, learn, and co-evolve with their environments. This creates path dependence: early events and early choices shape what becomes possible later, even when later conditions look similar. It also creates sensitivity to context: a small intervention can produce a large effect in one setting and almost none in another. (Waldrop, 1993) further emphasises that complex systems exhibit characteristic features such as non-linearity, distributed control, adaptation, and emergent order, meaning that outcomes cannot be straightforwardly inferred from individual components alone. This reinforces the point that meaningful explanation requires attention to interaction structure and mechanism, not only to aggregated indicators or static snapshots of system state.

Meadows & Wright (2008) provides a complementary systems view built around feedback loops, stocks and flows, delays, and leverage points. Feedback loops generate non-linear behaviour. Reinforcing loops amplify change, while balancing loops resist it. Delays between action and effect can produce oscillation and policy resistance. Meadows' leverage-point logic is relevant for SDG implementation because it highlights that system behaviour is often shaped more by information flows, institutional rules, incentives, and goals than by parameter changes. This is consistent with a focus on implementation pathways, where institutional design choices can determine what becomes feasible and what becomes recognised.

Snowden & Boone (2007) distinguish decision contexts in the Cynefin framework, including complex contexts where cause and effect can only be understood retrospectively and where adaptation and learning are essential. Many SDG-relevant transformations fit this description: multi-stakeholder interventions unfold over long horizons, and the same formal commitment can lead to different outcomes depending on capacity, enforcement, coordination, and external conditions.

A complexity lens is useful here not as decoration, but because it clarifies what an analytical model must be able to represent. Implementation systems contain conditional branching, where different futures become available depending on whether certain requirements are met. They contain path dependence, where early capability choices enable or prevent later outcomes. They contain threshold effects, where partial progress does not translate into recognised outcomes until multiple conditions are satisfied. These are structural features of the system, and they are difficult to capture in approaches that rely only on indicator correlations or abstract interaction scores.

2.5.2 Evolution of SDG network modelling approaches

Network-based approaches to SDG analysis grew from the recognition that the goals and targets are interdependent and that governance needs tools that make these interdependencies visible. Over the

last decade, SDG network modeling has progressed from semantic representations to statistical association networks and, more recently, to limited use of multilayer architectures. This progression has improved descriptive power, but it has not resolved a more basic limitation: most models remain focused on interactions among SDG elements rather than on implementation pathways that produce outcomes.

Le Blanc (2015) offered one of the earliest demonstrations of using network science in the SDG context by linking targets based on textual overlap and shared thematic content, showing that the SDGs could be interpreted as a network rather than a list. Nilsson et al. (2016) introduced a structured interaction scoring approach that distinguishes synergies from trade-offs on a scale, providing a vocabulary for policy coherence. These expert and semantic approaches can reveal how the SDG agenda is framed and where policymakers perceive interactions, but they do not establish mechanisms. Co-mention in text and expert scoring can indicate plausible relations, yet they can also reflect framing conventions, disciplinary emphasis, and the limits of what is visible to evaluators.

In parallel, statistical approaches have emerged using indicator data to infer networks of association. Pradhan et al. (2017) analysed correlations across large cross-country datasets and reported broad patterns of synergies and trade-offs. Lusseau & Mancini (2019) showed that such patterns vary by income level, suggesting that SDG interaction structure depends on development stage and context. These approaches have the advantage of being grounded in observed data patterns rather than in purely interpretive relations. They also allow comparisons across countries and time. Their core limitation is interpretive: statistical association is not the same as causal dependence. Correlation-based networks cannot by themselves identify which actions produced which changes, whether the relation is direct or mediated, or whether both are driven by a third factor.

Conceptual work has argued for stronger systems and complexity framing. Lim et al. (2018) emphasised that SDG interactions should be understood through feedback loops, causal pathways, and cross-scale linkages. This line of work is important because it moves the discussion toward mechanisms and dynamics. Yet in practice, many studies remain static and interaction-oriented. They map how goals appear to relate, but not how outcomes are produced under constraints.

A smaller subset of SDG network studies explored more complex architectures. Sebestyén et al. (Sebestyén et al., 2019) used multiplex ideas to explore how relations differ depending on data sources or relation types, while keeping indicators as the node basis. Bellantuono et al. (2022) introduced a heterogeneous multilayer approach that links indicators, targets, and goals across layers, making the hierarchical SDG structure explicit. These studies demonstrate that the field recognises the limitations of monoplex models and is experimenting with richer structures. Still, even when architecture becomes more sophisticated, the modeled system often remains the formal SDG framework rather than the implementation system, meaning that actors, capabilities, contracts, verification, and institutional processes remain outside the graph.

Horvath et al. (2022) synthesise SDG interaction methods across conceptual, qualitative, quantitative, and integrated approaches, and highlight recurring challenges in capturing causal mechanisms, dynamics, and context. Taken together, the evolution of SDG network modeling shows a field that has become more technically varied while remaining largely focused on SDG interactions rather than on implementation feasibility.

This distinction matters for the thesis. Interaction networks describe how SDG elements appear to move together or conflict. Implementation networks represent the pathway structure by which outcomes become reachable under conditions, dependencies, and verification. The analytical questions are different, and the ontological choices required for modeling are different.

2.5.3 Multilayer and higher-order networks for implementation analysis

Multilayer network theory provides formal tools for representing systems where relations are not all of the same kind and cannot be meaningfully collapsed into a single aggregate network without losing essential information. This is especially relevant for implementation systems, where contractual conditions, operational dependencies, verification relations, and attribution links function differently.

Kivela et al. (2014) provide a formal foundation and terminology for multilayer networks. They distinguish multiplex networks, where the same node set appears across layers with different edge types, from more general multilayer frameworks where node-layer tuples allow different nodes and inter-layer coupling. This matters for SDG analysis because different relations often operate on different semantics and time horizons. Treating them as one edge set can create category errors and produce misleading inferences.

Boccaletti (2014) analyse the structure and dynamics of multilayer networks and show that coupling between layers can change system behaviour compared with single-layer analysis. Diffusion, robustness, and cascading effects can behave differently depending on how layers interact. For implementation systems, this suggests that constraints in one relational domain, such as finance conditionality, can alter behaviour in other domains, such as capability development or outcome verification, in ways that are not visible if the system is represented as a single layer.

Multilayer thinking has been influential in sustainability science more broadly. Bodin et al. (2019) argue that social-ecological systems require network approaches that capture multiple types of interdependence and that many policy-relevant conclusions can be distorted when single-layer simplifications are used. Sayles et al. (2019) develop a typology for social-ecological networks that distinguishes multiplex, multilevel, and multidimensional structures, each suited to different questions and system configurations.

For this thesis's purpose, multilayer networks are not introduced as an abstract technical preference. They provide a way to represent multiple relation types while preserving their conceptual separation. This is a direct response to the implementation gap documented in SDG network science. If SDG implementation depends on conditionality, interdependent capabilities, verification, and recognition, then a framework that collapses these into one relation type would not be able to express how pathway feasibility is structured, a limitation that can be overcome using a multilayer approach.

Standard graphs model pairwise relations. Many sustainability outcomes, however, require coordinated action by more than two actors simultaneously, or depend on group-level arrangements such as multi-party agreements, certification schemes, or collective governance. Higher-order network approaches such as hypergraphs represent these group interactions explicitly, with hyperedges connecting multiple nodes at once (Johnson, 2013).

Battiston et al. (2020) review higher-order network structure and dynamics and show that diffusion, contagion, and coordination can behave differently when interactions occur in groups rather than as sums of pairwise ties. In SDG contexts, this is relevant because many outcomes depend on joint compliance and mutual recognition: a standard-setter, an auditor, a producer, and a financier may each be necessary for an outcome to be recognised and rewarded.

The diagnostic evidence from SDG network science indicates that higher-order representations are not currently used in this domain. This absence is understandable: most SDG networks are constructed from texts or indicator datasets that naturally yield pairwise associations. Higher-order modeling also raises practical demands in data structure and method selection. For this thesis, hypergraphs are therefore treated as relevant background, rather than as a required modeling choice. Their main role here is conceptual: they underscore that coordination requirements are real structural features of implementation systems, even when they are represented using simpler architectures for tractability.

2.5.4 Diagnostic framework, identified gap, and positioning of this thesis

To move beyond general and possibly non-systematic critique, Pasishnyk & Lopes (2025) developed an ontology-based diagnostic framework and applied it systematically to a corpus of 25 peer-reviewed SDG network studies. The purpose was to make representational choices visible, comparable, and assessable.

The diagnostic framework organises modeling into eight steps across four phases: Framing (defining the system and research questions), Abstraction (specifying what the network represents), Conceptualization (defining nodes, edges, and architecture), and Analysis (selecting methods and mapping data to the model). The framework is grounded in the dual-theory view of (Brandes et al., 2013): network analysis is meaningful only when there is coherence between the domain theory used to define ontological entities and the network theory used to instantiate nodes and edges and to analyse them.

Across the analysed corpus in (Pasishnyk & Lopes, 2025), two paradigms dominated. A semantic and expert-based paradigm infers relations from text, policy documents, literature, or expert scoring. A statistical paradigm infers relations from indicator data through correlations, Granger-style approaches, or related econometric methods. These paradigms differ in evidence base, but they share a fundamental limitation: both overwhelmingly model SDG elements themselves rather than implementation systems that produce outcomes.

The most consequential empirical result is that 24 of the 25 studies, 96% of the corpus, represent only the formal SDG framework (goals, targets, indicators, or composites of these) and do not represent implementation actors, organisational capabilities, contractual conditions, verification arrangements, or institutional processes as network elements. In other words, implementation is treated as outside the model, either as contextual narrative or as an implicit assumption. This is not a minor omission, it is a structural feature produced by how nodes and edges are defined in the existing literature.

The diagnostic also found strong architectural concentration. Most studies use monoplex networks with one node type and one edge type, sometimes weighted or directed but still structurally homogeneous. Only a small number use multilayer ideas, and none employ higher-order representations such as hypergraphs despite the prevalence of multi-actor coordination in SDG delivery.

Analytically, most studies rely on standard centrality measures, clustering, community detection, or descriptive visualization. These tools can produce useful descriptive insights, for example, highlighting which targets appear highly connected in expert-coded interaction networks or which indicators co-vary strongly across contexts. Yet the diagnostic demonstrates that such insights are constrained by ontological commitments. When the model's elements are SDG categories and the edges are co-occurrence or correlation, the model cannot answer implementation questions about feasibility, sequencing, bottlenecks, or conditional progression.

The diagnostic results serve as a grounded basis for the research gap developed at the end of this chapter. The gap is not that SDG network studies are unaware of implementation, but that implementation is not represented structurally in the models, which limits what those models can claim.

The literature on SDG governance and implementation emphasises that the SDGs are not simply a measurement system. They are a global commitment framework that must be translated into operational change through institutions, resources, and coordination. The sustainable finance literature shows that capital mobilisation often operates through binding conditions and verification expectations that shape what is implemented and what is recognised. Network science provides formal tools for representing interdependence, albeit SDG network applications have largely focused on interactions among SDG categories rather than on the implementation systems that generate outcomes.

These strands converge on a shared point: if one wants to explain why SDG progress stalls, or to analyse how outcomes might become feasible, one must model the structures that govern implementation, not only the interactions among SDG indicators or targets.

This convergence also clarifies a vocabulary discipline for the thesis. Commitments are not outcomes. Indicators are not operational states. Verification is not a reporting add-on. It is part of the institutional machinery that determines which outcomes are counted, and therefore which outcomes are incentivised. If these distinctions are conceptually important, then they must also be ontologically identified and representationally respected in modeling.

The diagnostic evidence establishes that SDG network science has built a substantial body of work on interactions among SDG elements, using semantic and statistical paradigms and increasingly using network measures to prioritise or cluster goals and targets. What it has not built is an approach that structurally represents implementation mechanisms, especially in contexts where finance conditionality and verification determine what becomes feasible and recognised.

This gap has direct analytical consequences. Interaction models can suggest where synergies and trade-offs appear, but they cannot assess reachability under conditions. They cannot diagnose bottlenecks in capability building or verification. They cannot represent branching pathways where different futures depend on compliance, evidence, and recognition. These are not secondary details in finance-enabled implementation systems. They often determine whether an outcome can be claimed at all.

This thesis responds to the methodological gap by developing an implementation-grounded network framework that represents finance conditions, implementation dependencies, verification relations, and SDG attribution within one coherent structure. This contribution is methodological as it provides a way to analyse feasibility and pathway structure, rather than only correlations or interaction scores.

The framework's design follows three commitments implied by the literature. First, it preserves the distinction between domains that operate differently, finance conditionality, organisational capability building, operational outcomes, verification and recognition, and SDG attribution. Second, it uses a multiplex or multilayer logic to represent different relation types as distinct layers, avoiding conceptual collapse. Third, it treats verification and recognition as decision points that condition pathway progression, rather than as assumptions.

The underlying stance aligns with design-oriented methodological traditions in which knowledge is produced through building and evaluating an analytical artefact and showing its utility for a class of problems. Validity is grounded in transparency of modeling choices, traceability to evidence, and coherence between the system being represented and the structure of the representation. The case application in later chapters demonstrates how the framework can be instantiated using documented transaction and verification materials and how it can reveal bottlenecks and constraints that are invisible in interaction-oriented SDG networks.

Taken together, this chapter provides the conceptual bridge from network science and complexity foundations to the thesis's modeling choices. It explains why a framework that represents implementation pathways, conditional constraints, and verification gates is not simply a different network model, but a different answer to a different question: not "how do SDGs relate," but "under what conditions can outcomes become feasible, verifiable, and attributable."

Diagnostic Review of SDG Network Approaches

Building on the conceptual foundations and methodological landscape reviewed in the previous chapter, this chapter undertakes a systematic diagnostic examination of how network science has been applied to the analysis of SDG interactions, with specific attention to what existing approaches make analytically visible and what they necessarily exclude. The analysis reveals persistent limitations that constrain both the analytical validity and practical utility of current approaches, setting the stage for the implementation-grounded framework developed in Chapter 4.

3.1 The Challenge of Modeling SDG Interdependencies

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 (Pradhan et al., 2017). For instance, biodiversity loss and climate change are increasingly recognised as outcomes emerging from social and ecological interactions (Selomane et al., 2019), potentially impacting food security and community well-being. Analytical efforts to map SDG interactions have grown in recent years, with comprehensive overviews provided (Bennich et al., 2020; Issa et al., 2024; Miola et al., 2019)(Miola et al., 2019) (Issa et al., 2024) yet translation into practice remains limited (Breuer et al., 2022; Horan, 2022)(Horan, 2022). A science-based understanding of how synergies and trade-offs emerge is critical for making the SDGs operational in real-world contexts (Donoghue & Khan, 2019), particularly with the 2030 deadline approaching rapidly.

This becomes increasingly important considering scenario-based planning frameworks (van Vuuren et al., 2022) and transformation-oriented strategies (Turnheim et al., 2020). Operationalizing these strategies remains a challenge, as without adequate grounding in sustainability pathways, models may oversimplify system dynamics (Sachs et al., 2019).

¹ Substantial part of the content of this chapter has been published in (Pasishnyk & Lopes, 2025).

Network science is the study of systems that can be represented as collections of interconnected entities (nodes) and their relationships (edges), using mathematical and computational tools (Brandes et al., 2013). This formalism has proven particularly powerful for analysing systems with nonlinear interactions, emergent properties and multiple scales of organisation. In sustainability contexts, network science offers at least three advantages: (1) explicit representation of interdependencies that traditional reductionist approaches tend to miss, (2) identification of critical leverage points and cascading effects through centrality and connectivity analysis, and (3) quantitative assessment of system resilience and vulnerability (Barabási, 2013); (Bodin et al., 2019).

Although network science provides valuable tools to reveal and structure such interactions, 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, such as ecological connectivity and institutional arrangements, into coherent network representations (Brandes et al., 2013). The challenge is 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 (Donoghue & Khan, 2019); (Sachs et al., 2019). 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 (Brandes et al., 2013). In a sample of 25 studies, selected via a scoping review process, its large majority abstract SDGs as targets or indicators; one specifies a multiplex structure and another links distinct SDG levels in a heterogeneous multilayer (network-of-networks) design. None of these studies 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 (Barabási, 2013). These decisions shape not only the network's structure but its interpretive power, affecting what dynamics become visible and which remain hidden (Bodin et al., 2019). 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 et al., 2013), requiring explicit integration of domain expertise with mathematical theory. Our approach treats network science not as a metering or 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 the 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 analysing 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 in objective 2 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 (Coenen et al., 2022); (Aly et al., 2022).

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 and targets under goals, reflects political compromise rather than scientific logic, obscuring the interconnections the 2030 Agenda deems fundamental (ICSU, 2015).

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 (Bennich et al., 2020); (Nilsson et al., 2018). Even when linked to broader sustainability domains like food systems or ecosystem services, formal system-based methodologies are rarely applied (Allen et al., 2019). This pattern reflects a persistent tendency to address poverty, climate, biodiversity, and inequality as discrete agendas, despite well-documented interdependencies (Liu et al., 2015; Weitz et al., 2018)(Liu et al., 2015).

The SDGs exhibit the hallmarks of a complex system: multi-scale interactions, feedback loops, emergent properties, and adaptive behaviours (Newman, 2010). 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; and climate nodes would influence both production capacity and price volatility through feedback loops that operate on different timescales. In contrast, current approaches typically model SDG 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 (Bennich et al., 2020); (Allen et al., 2019).

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 (Nilsson et al., 2018); (Liu et al., 2015). The recent growth of research on “SDG interactions” signals recognition of this need, yet many approaches remain conceptually underdeveloped and methodologically inconsistent (Bennich et al., 2020); (Allen et al., 2019).

Here, we examine SDG interactions through network models, focusing on the assumptions embedded in their construction. Network science, which centres on relationships, structures and dynamics, offers a natural lens for analysing such complexity, provided sustainability phenomena are carefully translated into network form (Bodin et al., 2019); (Brugere et al., 2016). By applying a structured, theory-grounded framework, we aim to advance both conceptual clarity and analytical rigour in the study of SDG interactions.

Despite these advances, the SDG interaction literature still lacks a methodological framework that makes ontological assumptions and modelling choices explicit, comparable, and transparent across studies. To address this gap, we propose an eight-step framework for evaluating SDG network models and apply it to a corpus of 25 peer-reviewed studies. This approach clarifies what each model represents, how representational choices structure analytical outcomes, and where methodological patterns converge or diverge. By consolidating these elements, the article establishes a clear basis for systematic comparison, evidence synthesis, and more implementation-relevant SDG network modelling.

3.2 Development of the Ontology-Based Network Framework

The UN SDGs comprise 17 goals, 169 targets and 231 indicators that provide a global monitoring framework rather than a scientific model of how sustainability outcomes emerge (UN DESA, 2025); (ICSU, 2015). Prior efforts to interpret this structure as a system follow three main strands: semantic or expert-based mappings of textual co-occurrence or policy narratives; indicator- or correlation-based approaches that infer interactions from statistical associations; and network-based studies that link SDGs using formal structures from the UN hierarchy. The references belonging to each of these strands are listed in Table 1.

Table 1. Main strands in SDG network related literature

Strand	References
1. Semantic mappings	(Le Blanc, 2015); (Lim et al., 2018); (McGowan et al., 2019); (Song & Jang, 2023); (Pham-Truffert et al., 2020); (Jaramillo et al., 2019); (Dalampira & Nastis, 2020); (Mainali et al., 2018); (Dawes, 2020); (Allen et al., 2019); (Weitz et al., 2018).
2. Indicator or correlation-based	(Cao et al., 2023); (El-Maghrabi et al., 2018); (Dörge et al., 2018); (Bali Swain & Ranganathan, 2021); (Zhou et al., 2017); (Türkeli, 2020); (Lusseau & Mancini, 2019); (Androna et al., 2024); (Laumann et al., 2022); (Xiao et al., 2022); (Xiao et al., 2024); (Xing et al., 2024).
3. Formal structures from UN hierarchy	(Sebestyén et al., 2019); (Bellantuono et al., 2022).

Beyond these conventional approaches, recent studies have explored multilayer network architectures (Sebestyén et al., 2019); (Bellantuono et al., 2022). These approaches provide useful descriptive insights but remain tied to the formal SDG architecture and rarely represent the actors, mechanisms or processes through which implementation occurs. In other words, across the semantic, statistical, formal-hierarchy, and even multilayer strands, most SDG network work models relations among SDG elements rather than the implementation systems that generate outcomes. This creates a persistent methodological gap between analytical models and real-world sustainability systems, which directly motivates the ontology-based, implementation-grounded network framework developed in this study.

Network science offers tools for representing relational structures in interconnected systems, which is essential for analysing SDG interdependencies (Brandes et al., 2013); (Brugere et al., 2016). However, existing applications of network science to SDGs often rely on simplified abstractions that obscure underlying mechanisms, creating a persistent gap between analytical models and real-world sustainability challenges (Dawes, 2020).

To address this gap, we developed 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 dual-theory perspective distinguishes between (1) domain-specific theories used to abstract real-world phenomena into relational concepts and (2) mathematical network theories that examine structural properties independent of substantive content. This perspective highlights that abstraction requires ontological commitments to scientifically relevant features (Brandes et al., 2013), which shape both the structure and interpretive power of resulting network models (Bodin et al., 2019).

We term this an ontology-based framework because it systematically addresses the fundamental question: “What entities and relationships constitute the system we seek to model?” In philosophy of science, ontology concerns the nature of being and existence, in particular what kinds of things exist in a given domain and how they relate (Guarino, 1998; Guarino et al., 2009); (Guarino et al., 2009). An ontology-based modelling framework therefore requires researchers to, using problem-domain specific theories, make explicit choices about what entities exist, how entities are bounded and aggregated, which types of relationships connect them, and how abstract representations map to real-world implementation systems.

The development of the framework followed four procedural steps:

(1) Conceptual foundations: We reviewed literature from SDG governance, systems thinking, and complex systems to identify analytical challenges associated with the SDGs’ hierarchical architecture. Unlike traditional disciplinary applications, sustainability research requires combining ecological connectivity, socio-economic processes, and institutional arrangements within coherent network representations (Brandes et al., 2013). In SDG research specifically, most network analyses treat goals, targets, or indicators as abstract nodes without representing mechanisms of sustainability transformation (Bennich et al., 2020); (Sachs et al., 2019).

(2) Integration of network science theory: To ensure conceptual rigour, we applied the Brandes et al. (Brandes et al., 2013) dual-theory framework, recognising that these decisions determine which system features become analytically visible and which remain hidden (Bodin et al., 2019).

(3) Structuring methodological phases and steps: Based on these foundations, we organised the modelling process into four phases, namely Framing, Network Abstraction, Network Conceptualisation, and Network Analysis, each comprising explicit analytical steps. The framework is presented in **Error! Reference source not found..**

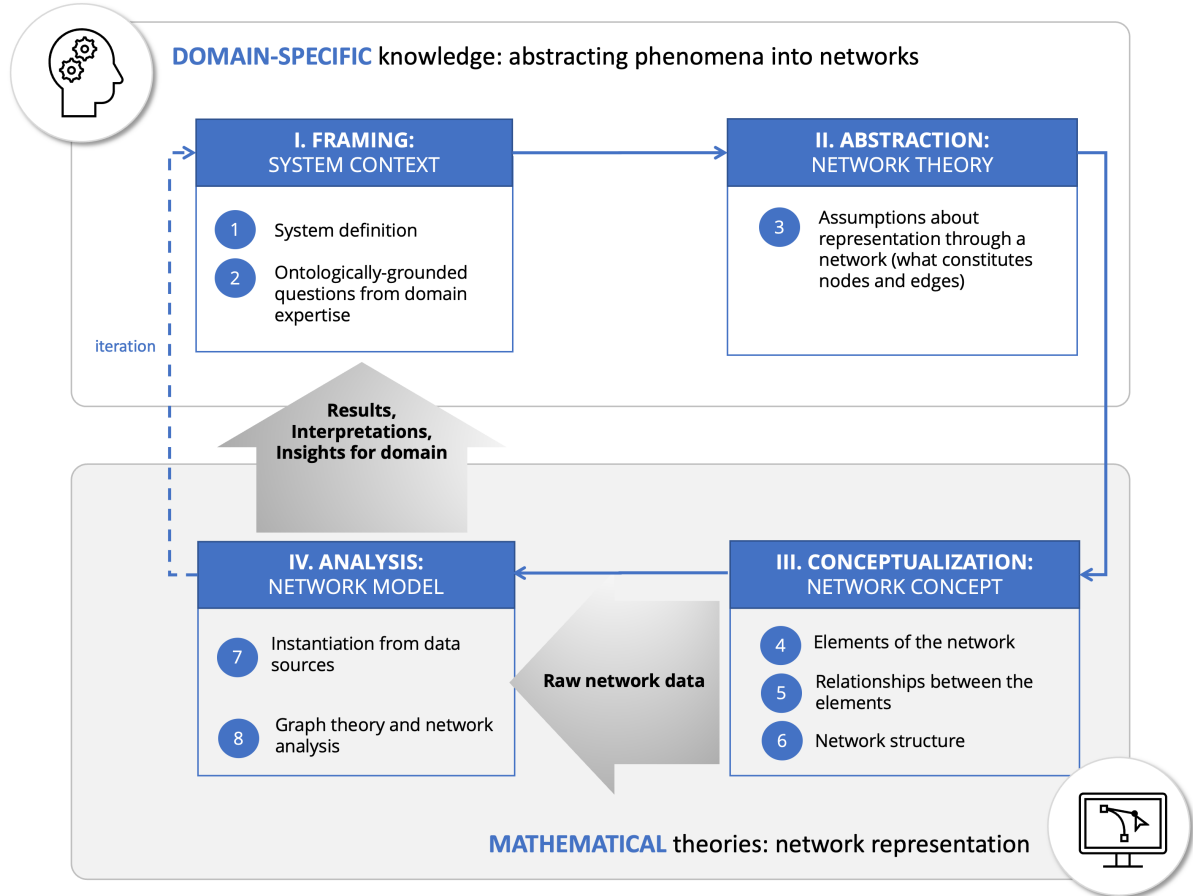


Figure 1. The Scientific Method for Network Modelling: From Phenomena to Network Models. Our framework distinguishes four methodological phases (shown in blue boxes), each involving deliberate theoretical and analytical choices, and two operational processes (shown as grey arrows) that implement these choices without introducing new methodological decisions. Data collection operationalizes the conceptual design, while interpretation translates results back to domain insights, potentially triggering iteration.

Operationalisation. For each SDG network study, the eight analytical steps were applied as a coding protocol. Step 1 captured how the authors defined the system and its boundaries; Step 2 identified how domain assumptions shaped problem framing; Steps 3-4 documented what entities and relationships were abstracted into nodes and edges; Steps 5-6 recorded structural specifications such as directionality, weighting, and architectural form (monoplex, multiplex, multilayer); Step 7 captured the analytical techniques and metrics; and Step 8 identified how variables and data sources were mapped onto the network model. Each step was coded independently and later synthesised into the A/B/C tiers to assess transparency, integration of domain knowledge, and representational fidelity.

Phase I. Framing defines the observed phenomenon, system boundaries, and research questions:

System definition: identifying the real-world system (s) to be analysed.

Ontologically grounded questions: formulating research questions reflecting domain-specific assumptions about entities and relations.

Phase II. Network Abstraction translates real-world phenomena into abstract relational constructs:

Assumptions about representation: determining what constitutes nodes and edges based on theoretical interpretation.

Phase III. Network Conceptualisation provides mathematically precise modelling specifications:

Elements of the network: defining entities (nodes).

Relationships between elements: specifying the nature of connections (edges).

Network structure: selecting architectural forms (directed/undirected, weighted/unweighted, monoplex/multiplex).

Data collection (grey arrow in Figure 1) operationalises this conceptual structure.

Phase IV. Network Analysis applies mathematical techniques to reveal system properties:

Theory of network representation and analysis: selecting appropriate algorithms or metrics.

Variables as network data: identifying and interpreting data elements feeding the network model.

Iteration occurs when analytical insights expose mismatches or new dynamics requiring refinement.

(4) Iterative refinement and validation.

The framework was iteratively refined through cross-reading of SDG interaction studies, comparison with methodological guidelines in network science, and pilot applications across sustainability domains including food systems, climate-biodiversity linkages, and policy networks. This ensured face validity, conceptual coherence, and broad applicability.

3.3. Evaluation Framework for Network Science Application to SDG studies

We systematically examine how network science has been applied to model SDG interdependencies, developing a classification framework that reveals methodological patterns and assumptions. Our goal is not to grade individual studies, but to analyze the choices researchers make when translating sustainability phenomena into network form. Building on (Brandes et al., 2013) dual-theory approach,

which links domain-specific knowledge with mathematical network theory, we evaluate how network models are constructed to represent sustainable development dynamics.

3.3.1. Identification and Selection of SDG Network Studies

We analysed 25 peer-reviewed studies applying network science to SDG interactions. The selection of these studies was made using a scoping review methodology process. This process and its details (databases, query strategies and exclusion criteria) are available in Annex 1.

Our goal is not to grade individual studies, but to analyse the choices researchers make when translating sustainability phenomena into network form.

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 (Coenen et al., 2022); (Aly et al., 2022). Our selection builds on the state-of-the-art review by (Bennich et al., 2020), 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.

We excluded conceptual typologies and narrative frameworks that do not construct or analyze a graph. (Nilsson et al., 2018) is therefore discussed in the text but not included in application of the classification framework. Bibliometric studies were excluded unless the nodes correspond directly to SDG entities and the analysis interprets their interrelations as SDG interactions rather than publication patterns.

Despite the availability of network tools for multi-scale, multi-relation phenomena, most SDG applications model abstract goal or target structures, while implementation pathways, actors, and processes that drive outcomes are less frequently represented.

3.3.2. Coding Procedure and Analytical Approach

We introduce a three-tier classification (Options A, B, C) that captures differing degrees of integration between substantive domain knowledge and formal modeling (Figure 2):

- Tier A denotes descriptive or loosely structured approaches with weak domain-network alignment.
- Tier B reflects intermediate approaches with moderate theoretical engagement and clearer empirical translation.

- Tier C represents integrated approaches with high conceptual alignment between phenomena, model, and analysis, often drawing on formal theories or causal logic.

This classification captures different methodological approaches rather than strict linear progression. While in many cases Tiers A, B, and C frequently represent increasing integration between domain knowledge and network formalization, this is not universal across all eight steps. In some steps progression reflects conceptual depth, in others it captures alternative design choices rather than “better” or “worse” practice.

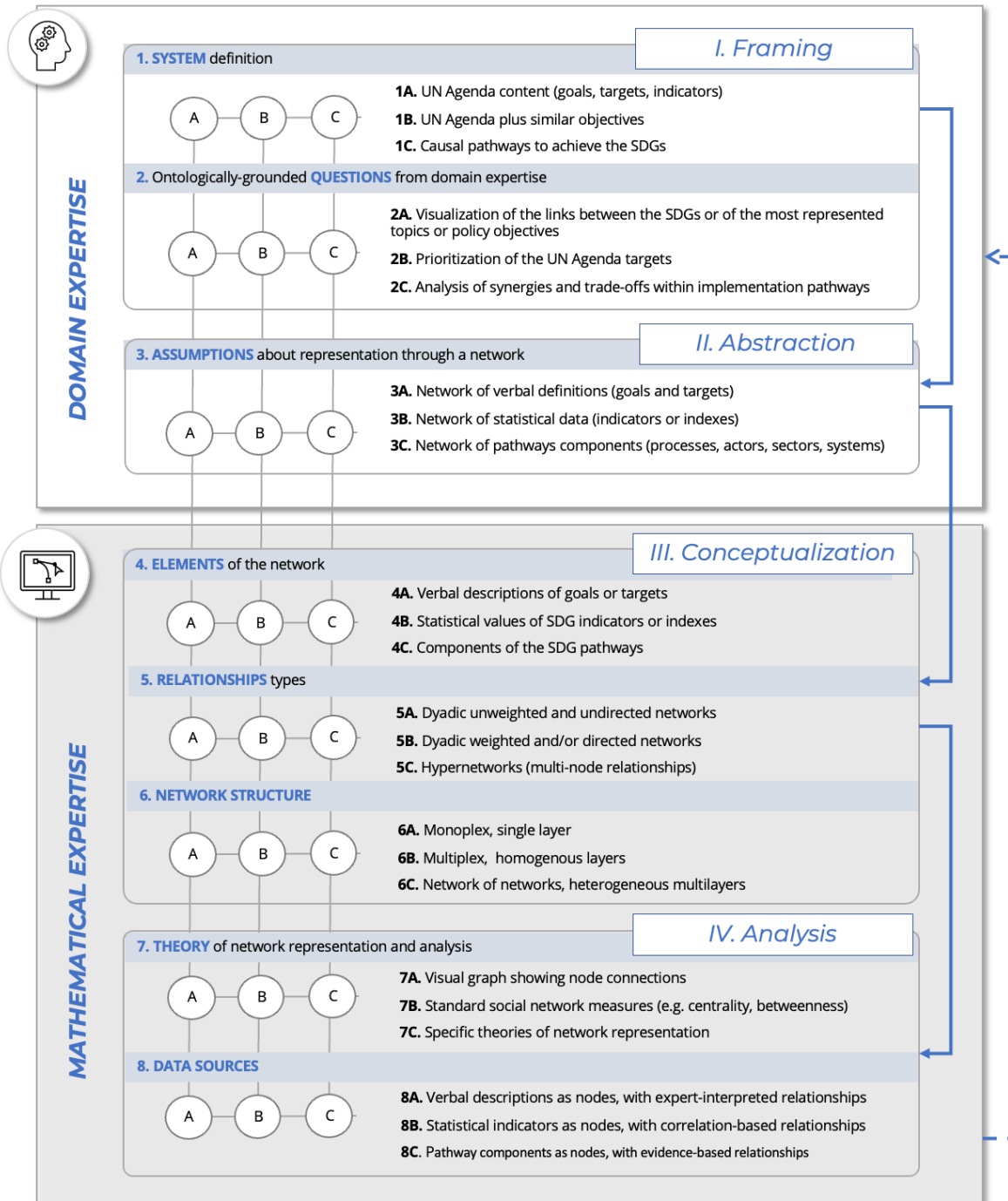


Figure 2. Classification framework for evaluating SDG network studies across four methodological phases and eight analytical steps. Tiers A, B, and C represent increasing levels of theoretical integration and implementation relevance. Each step distinguishes how studies transform sustainability phenomena into network structures, from initial system framing through data instantiation. The framework reveals that while Tier A and B approaches dominate current SDG network research, Tier C approaches grounded in implementation pathways remain largely absent. (Source: (Pasishnyk and Lopes, 2025).

This framework does not rank studies by sophistication. Instead it clarifies the ontological and methodological commitments embedded in each approach, showing how conceptual choices determine what aspects of sustainability systems are illuminated or obscured by network representations. In doing so, it enables more systematic comparison across an increasingly diverse body of work and supports a structured meta-analysis of methodological practice. It reveals patterns in how studies move from observed phenomena to analytical outputs, and whether those transitions maintain coherence between theoretical framing, empirical content, and network representation. Importantly, it also identifies where studies fall short, for example, by treating networks as purely technical tools, or by relying on descriptive system framings without analytical follow-through.

To evaluate modelling choices, we developed a coding rubric aligned with the eight analytical steps of the framework (Figure 2). Coding captured both explicit methodological decisions and implicit assumptions.

Coding structure. Each study was coded across the four phases and eight steps: (1) System definition, (2) Ontologically grounded questions, (3) Assumptions about net-work representation, (4) Elements that represent system's components, (5) Relation-ships between the elements, (6) Network structure, (7) Theory of network representa-tion and analysis, and (8) Data sources. Each step was assigned a tier (A, B, or C) based on the degree of theoretical grounding, methodological transparency, and integration of domain knowledge demonstrated.

Extraction of modelling decisions. For each of the 25 studies, we systematically extracted all information relevant to the modelling choices embedded in their network designs. Extraction followed the eight analytical steps of the framework to ensure consistency and comparability across studies. For each step, we identified the specific decisions authors made, along with any explicit justifications or implicit assumptions reflected in the text.

Specifically, we recorded:

- System definition (what the authors define as the SDG system, its boundaries, and units of analysis).
- Problem framing (how research questions reflect assumptions about entities and relationships).
- Representational assumptions (how nodes and edges are defined, including any theoretical rationale).
- Node specifications (what types of entities are represented and how they are aggregated or classified).
- Edge specifications (the basis for defining relationships, including directionality, weighting, and evidence criteria).

- Network architecture (whether the model is monoplex, multiplex, multilayer, or otherwise structured).
- Analytical techniques (algorithms, metrics, and computational procedures used to analyse the network).
- Data mapping (how variables, indicators, or textual elements are converted into network inputs).

Where relevant, text was extracted verbatim to preserve the authors' terminology, and each decision was then assigned a Tier A/B/C classification. All extracted evidence, coding notes, and tier assignments are provided in Annex 2. Coded studies were grouped into methodological archetypes based on shared characteristics in network construction approaches (semantic/expert-based vs. indicator/statistical) and architectural choices (monoplex vs. multilayer). Comparative analysis across the tier assignments enabled identification of dominant patterns, rare variants, methodological gaps, and underexplored opportunities in SDG network model-ing.

3.3.3. Phase I: Framing

The initial phase of building a network model sets its boundaries and scope, identifying the system under study and the key questions it aims to address, thereby laying the groundwork for a focused analysis. For SDG applications, this may involve framing the observed system as the formal UN goal content or statistical datapoints of SDG indicators, the broader policy ecosystem, or the causal mechanisms to achieve the goals. Research questions must clarify what aspects of SDG interconnections the network will represent, such as visualizing goal relationships, identifying priority targets, or understanding implementation synergies. Understanding data provenance is essential because measurement uncertainties are frequently neglected in network studies (Peel et al., 2022).

Step 1. System definition: We classify how studies define the "system of SDGs":

- [A].** UN Agenda content (goals, targets, indicators);
- [B].** UN Agenda plus similar objectives;
- [C].** Causal pathways to achieve the SDGs.

Tier A limits the system to the formal 169 targets and 231 indicators structured under 17 goals. Tier B expands to include related frameworks such as planetary boundaries, human rights objectives, or national development plans that align with but extend beyond the official SDG framework. While tiers A and B dominate existing literature, tier C offers significant analytical potential. Causal pathways are detailed projections that simulate future conditions based on policy interventions, using back casting from desired outcomes to map strategic actions (Estoque, 2023). These pathways detail required actions, resources, technologies, and stakeholder engagement across system changes. Despite their analytical promise evident in frameworks like TWI2050 and Deep Decarbonization Pathways (Sachs et al., 2019; Szetey et al., 2021), our analysis reveals few network studies leverage these approaches: 24/25 studies are Tier A (UN Agenda as the system); 1/25 is Tier B (Androna et al., 2024); Tier C did not appear.

Step 2. Ontologically-grounded questions from domain expertise: Defining clear objectives for network modeling is crucial, as it shapes how the system is conceptualized and analysed. We classify research objectives as:

- [A].** Visualization of the links between the SDGs or of the most represented topics or policy objectives;
- [B].** Prioritization of the UN Agenda targets;
- [C].** Analysis of synergies and trade-offs within implementation pathways.

Tiers A and B reflect common approaches cited in SDG network literature. Tier A focuses on descriptive mapping to reveal connections, while Tier B seeks to identify which targets should receive priority attention based on their network position or influence. Tier C addresses current gaps by analysing complex interactions among SDG strategies, including the influence of new technologies (Bennich et al., 2020), sectoral dependencies and stakeholder dynamics (Estoque, 2023 ;Horan, 2022), and the role of the private sector alongside public policies. In our sample, prioritisation (Tier B) is the most common objective; mapping/quantification without prioritisation (Tier A) is less frequent.

3.3.4 Phase II: Abstraction

This phase involves distilling complex reality into a simplified representation, identifying the essential elements and relationships to be modelled. This phase requires ontological clarity defining (1) what constitutes nodes (e.g. goals, targets, actors), (2) what constitutes edges (e.g. correlations, causal pathways, governance ties), and (3) how global network structure is conceptualized (e.g. clusters, hierarchies, core-periphery patterns). Each choice encodes theoretical assumptions and constrains what can be inferred. The quality of these ontological commitments determines whether network

analyses merely describe structural features or yield deeper insights into sustainability dynamics. Network theory assumes that any cause, effect, or association between aspects involves something that can be represented as a network structure.

For SDGs, researchers must make these commitments explicit for each element. Individual entities might be goals, targets, indicators, or institutional actors. Pair-wise relationships could represent statistical correlations, causal pathways, governance connections, or resource flows. The global patterning might capture hierarchical goal structures, clustered thematic areas, or core-periphery implementation dynamics. Each set of choices creates fundamentally different network abstractions that embody distinct theoretical assumptions about sustainable development phenomena.

Step 3. Assumptions about representation through a network: Network abstraction requires explicit assumptions about what constitutes meaningful SDG interactions. We classify how studies approach this challenge:

- [A].** Network of verbal definitions (goals and targets);
- [B].** Network of statistical data (indicators or indexes);
- [C].** Network of pathway components (processes, actors, sectors, systems).

Tiers A and B reflect a focus on elements directly derived from the UN Agenda: Tier A treats the textual descriptions of goals and targets as the fundamental units, typically analyzing semantic relationships or policy coherence. Tier B shifts to quantitative representations, using indicator values or composite indexes to define the network structure. Tier C adopts a process-relational lens, capturing how diverse actors (e.g. government agencies, farmer organizations, investment funds) and systems (e.g. food production, conservation, education) interact to shape SDG implementation. In our evaluation, two patterns dominate: semantic or text-based representations (A) and statistical or indicator-based representations (B). Pathway or actor networks (C) are absent.

3.3.5. Phase III: Conceptualization

This phase transforms theoretical commitments made during abstraction into concrete analytical frameworks. It defines the structure of the network model's elements, relationships, and architecture, determining how the network will represent sustainability phenomena and support research objectives. For SDG-related models, this requires coherence between the network's structure, the domain-specific understanding of sustainable development, and the mathematical requirements for analysis. These decisions involve defining edge weights based on development theory, selecting between simple correlations or complex multi-goal interactions, and choosing structures that reflect both theoretical commitments and analytical intent rather than data convenience. A hypernetwork

might model policy interventions affecting multiple goals simultaneously, while weighted multiplex networks could capture both strength and diversity of goal interdependencies. These choices align with ontological commitments from abstraction and analytical questions from system framing, ensuring mathematical precision serves theoretical clarity.

Step 4. Elements of the network: Identifying the network's elements is a foundational step, as these nodes serve as the basic units through which sustainable development phenomena are represented and examined:

- [A].** Verbal descriptions of goals or targets;
- [B].** Statistical values of SDG indicators or indexes;
- [C].** Components of the SDG pathways.

Tier A refers to textual formulations of SDGs as articulated in the UN Agenda 2030, often used in co-occurrence networks or discourse-based mappings. Tier B uses the numerical values of SDG indicators, allowing the model to reflect temporal trends, correlations, or empirical patterns. Tier C reflects a more process-oriented approach, in which nodes represent elements such as sectors, actors, technologies, or interventions embedded in causal or implementation pathways.

Each choice reflects distinct ontological assumptions and directly affects the model's analytical implications. While verbal definitions may be useful for exploratory or normative analyses, pathway components offer more robust entry points for representing real-world dynamics, enabling deeper insights into implementation challenges and leverage points. In our evaluation, nodes are predominantly goals or targets (A), with a substantial minority at the indicator level (B); only one study (Sebestyén et al., 2019) mixes distinct node ontologies across SDG levels (C). No study defines nodes as pathway actors, sectors, or interventions.

Step 5. Relationships types: Network relationships determine how connections between elements are modeled:

- [A].** Dyadic unweighted and undirected networks;
- [B].** Dyadic weighted and/or directed networks;
- [C].** Hypernetworks (multi-node relationships).

Tier A represents the simplest form of network: symmetric relationships of equal significance, without direction or variation in intensity. Tier B introduces weight and/or direction, enabling the modeling of synergies, trade-offs, or causal flows, for example, where one SDG may influence another more strongly or asymmetrically.

Many sustainability challenges involve higher-order interactions beyond pairwise connections, for instance, coordination among public, private, and community actors in land-use systems. Hypernetworks (Tier C) use hyperedges to link multiple nodes simultaneously, capturing how a single intervention, such as agroforestry, can simultaneously contribute to the targets related to biodiversity, carbon sequestration, and rural livelihoods (Majhi et al., 2022; Battiston et al., 2020). In our study, dyadic, weighted and often directed edges (B) dominate (e.g., signed cross-impact, correlations, Granger, econometrics); a few early semantic mappings remain unweighted and undirected (A). Hyperedges (C) do not appear.

Step 6. Network structure: Network structures are classified by how they encode heterogeneity and cross-level dependencies:

- [A]** Monoplex (single layer),
- [B]** Multiplex, homogeneous layers,
- [C]** Network of networks, heterogeneous multilevel.

Monoplex networks (Tier A) contain a single node set and a single relation type. All links are structurally and semantically equivalent. This structure is analytically simple, yet it can miss dynamics that arise when multiple relation types or scales interact.

Multiplex networks with homogeneous layers (Tier B) repeat the same node ontology across several layers, for example the 17 SDGs replicated across different relation types, data sources, countries, or time slices. Inter-layer connections are identity or simple coupling between the same nodes. This structure captures distinct interaction types without changing the node type.

Networks of networks, heterogeneous multilevel (Tier C) combine layers that use different node ontologies, linked by explicit cross-level dependency edges. Typical examples include indicators linked to targets linked to goals, or actors connected to processes and ecosystems. This structure is suitable for sustainability systems that span social, ecological, and institutional domains and that require modeling of hierarchical or pathway dependencies. These distinctions follow (Aleta & Moreno, 2019) typology, which emphasizes matching network architecture to system complexity and heterogeneity. In our sample, monoplex dominates. We found one multiplex design (B) (Bellantuono et al., 2022) and one heterogeneous multilayer “network-of-networks” design (C) (Sebestyén et al., 2019). No hypernetworks were used.

3.3.6 Phase IV: Analysis

This final phase where the constructed model is examined and explored, utilizing various tools and techniques to understand the dynamics within the network, evaluate the interactions, and derive

insights related to the initial framing questions. For SDGs, this involves applying network metrics to understand goal interdependencies, identifying critical development pathways, and translating mathematical findings into actionable policy insights that address the initial framing questions.

Step 7. Theory of network representation and analysis: We classify analytical approaches by their theoretical grounding:

- [A].** Visual graph showing node connections;
- [B].** Standard social network measures (e.g. degree centrality, betweenness);
- [C].** Specific theories of network representation.

Tier A provides visual communication of SDG relationships but lacks analytical depth. Tier B applies established metrics, often borrowed from social media studies networks, though these may be conceptually ungrounded when applied without attention to sustainability-specific ontological commitments made during abstraction. Tier C employs formal theories, such as multilayer network theory for complex interdependencies, dynamic networks for modeling temporal change, or controllability theory to identify strategic intervention points. These approaches are chosen based on the characteristics of the sustainability system and the research questions being addressed.

In our sample, most analyses rely on standard social network measures (B). Only two papers apply specific formal theory: (Dawes, 2020) (self-consistency) and (Sebestyén et al., 2019) (multilayer theory).

Step 8. Data sources: We classify what data studies use to instantiate the network model:

- [A].** Verbal descriptions as nodes, with expert-interpreted relationships;
- [B].** Statistical indicators as nodes, with correlation-based relationships;
- [C].** SDG pathway components as nodes, with evidence-based relationships.

Tier A uses qualitative content from policy texts, establishing links through expert judgment or textual co-occurrence. While intuitive and accessible, this approach often lacks consistency and replicability. Tier B relies on quantitative indicator data and statistical techniques to define relationships, enabling empirical modeling but potentially obscuring causality or context. Tier C anchors variables in SDG pathway logic (e.g. stakeholders, sectors, technologies), where relationships are grounded in documented resource flows, institutional arrangements, or implementation mechanisms. This approach allows for deeper system modeling but requires robust domain-specific justification. Indicator datasets (B) slightly outnumber expert or semantic instantiation (A); pathway or implementation evidence (C) is absent.

Network model validity ultimately hinges on variable selection that reflects both theoretical coherence and empirical relevance, requiring domain expertise to preserve the structural and semantic integrity of the model.

3.4 Findings

3.4.1 Results of the Framework Application

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 (Figure 3): semantic/expert-based approaches (11 studies) and indicator/statistical approaches (12 studies), along with two rare multilayer variants (one multiplex and one heterogeneous multilayer), details provided in Table 1.

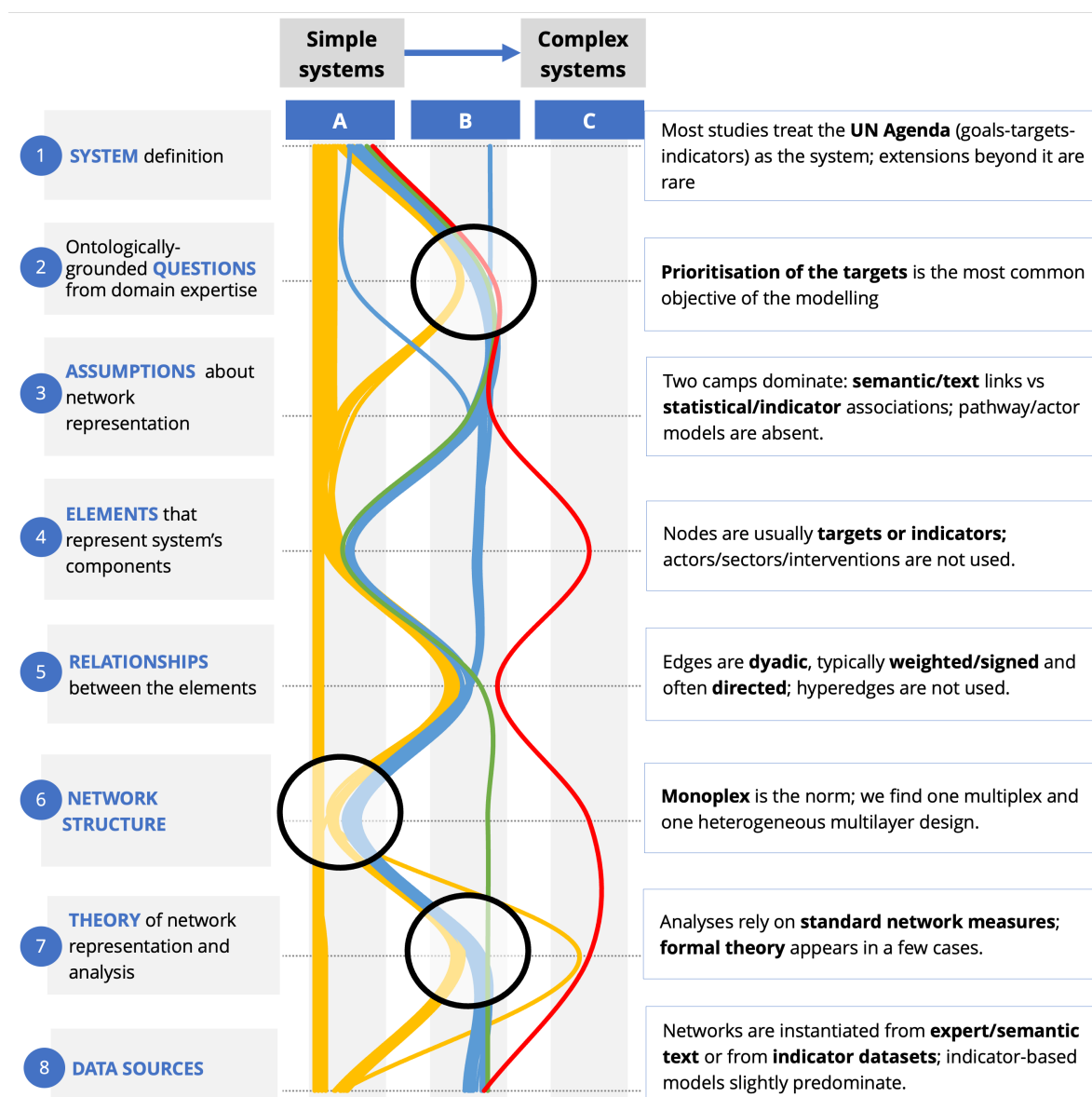


Figure 3. Results of SDG network modelling approaches classification. The classification framework reveals four patterns in approaching SDG network modelling. The semantic/expert-based group includes 11 studies (yellow); the indicator/statistical group includes 12 studies (blue); one study implements a multiplex model (green) and one a heterogeneous multilayer design (red). Black circles highlight common patterns: target prioritisation, monoplex structures and standard network measures.

Beyond the qualitative characterisation of modelling patterns, the tier assignments also reveal consistent quantitative tendencies (as shown in Table 2). Across the eight analytical steps, Tier A accounts from 62% to 88% of all classifications, depending on the step. Tier B represents 12% to 36% percent of classifications, concentrated in representational assumptions, analytical techniques and data sources. Tier C appears in no more than two studies per step, representing less than 10% of the total sample for every analytical dimension. These proportions provide a quantitative confirmation of the overall pattern: most SDG network studies rely on formal UN structures with limited integration of implementation mechanisms or domain-specific theory.

A complementary overview is provided in Table 2, which reports the distribution of studies across Tiers A, B and C for each analytical step. The pattern confirms that most studies fall into Tier A for system definition, research questions and structural specification, indicating reliance on formal SDG structures. Tier B is more common for representational assumptions and data choices, while Tier C is rare across all steps. No step shows more than two studies in Tier C, highlighting consistent gaps in mapping SDG interactions to implementation actors, mechanisms and processes.

Table 2. Distribution of studies across methodological tiers (A/B/C) for each of the eight analytical steps.

Analytical Step	Tier A	Tier B	Tier C
1. System definition	24	1	0
2. Ontologically grounded questions	8	17	0
3. Representational assumptions	11	14	0
4. Elements (nodes)	19	5	1
5. Relationships (edges)	3	22	0
6. Network structure	23	1	1
7. Representation and analysis	4	19	2
8. Data sources and variables	11	14	0

Eleven studies (yellow line, in Figure 3) construct semantic networks from policy texts, using expert elicitation, keyword co-occurrence, systematic literature synthesis, and text embeddings. Twelve studies (blue line, in Figure 3) 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 another 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 interactions 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.

3.4.2 Insights

This analysis highlights a persistent disconnect in how network science is applied to sustainable development. While SDG interlinkages are frequently modelled, 96% of the reviewed studies focus on abstract structures rather than the mechanisms through which sustainability transformations actually occur. By contrast, implementation-grounded systems frameworks explicitly represent actors, processes, and causal delivery mechanisms, enabling analysis of how interventions propagate through real-world development systems rather than remaining at the level of abstract goal interactions (Blair et al., 2021). This decoupling between analytical and real-world implementation limits the usefulness of these models for decision-makers, especially those allocating capital in support of sustainable outcomes.

These methodological gaps have concrete implications for SDG implementation systems. Indicator-based networks that treat goals or targets as nodes and rely on statistical associations can overstate correlations that do not correspond to actionable levers in implementation systems. For example, country-level SDG diagnostics that use network centrality to suggest “priority goals” risk directing attention toward highly connected indicators, even when the real constraints lie in specific sectors, agencies or financing mechanisms that the model does not represent.

Similarly, semantic networks that map co-mentions of goals in policy documents can be useful for communication and narrative framing, but they do not in themselves identify which ministries, firms or communities must coordinate to realise synergies. By contrast, ontology-based designs that include implementation nodes such as institutional actors, financial instruments, and ecosystem dependencies, can reveal where coordination failures, capacity gaps or misaligned incentives block or hinder progress on multiple goals simultaneously.

These observations suggest that SDG network models limited to formal structures may support discourse, but they are poorly suited for guiding operational decisions about where and how to intervene. 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 those 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.

Recent developments in social-ecological network (SEN) analysis further illustrate the potential of embracing a system-based perspective. For example, the typology proposed by (Sayles et al., 2019) 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.

3.4.3 Practical Implications

These improvements are not only relevant to academic modelling but are also critical for practical decision-making. Notably, they have potential relevance for actors engaged in implementation-oriented decision processes, such as governments, development partners and finance institutions. While our analysis does not assess current investment or lending practices, the conceptual implications are clear: analytical tools that reflect causal mechanisms and implementation dynamics are better aligned with the types of questions these actors typically confront. Models centered on formal SDG structures may support communication and monitoring, but they are less suited for identifying leverage points, diagnosing systemic bottlenecks or anticipating cross-domain effects.

Beyond SDG network modelling, approaches such as integrated fuzzy multi-criteria decision frameworks illustrate how complex criteria and trade-offs can be structured for operational decision-making (Blair et al., 2021; Tatarczak & Gola, 2025).

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 facilitates assessment of 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.

3.5 Limitations and Challenges

The framework also has practical limitations. Integrating domain knowledge with formal network structures, especially in Steps 2 and 4, requires sustained multidisciplinary collaboration that is often difficult to achieve. On the other hand, the eight-step structure may appear prescriptive, and some emerging approaches may not fit neatly into its four-phase design. Data constraints may also prevent studies from reaching higher-tier classifications. Finally, the assumption that greater methodological transparency and closer alignment with implementation systems improves decision relevance requires empirical validation through comparative assessment.

This study also has scope limitations. The final sample of 25 papers resulted from a Scoping-Review framework style screening of the broader SDG-network literature, with eligibility restricted to studies where SDGs or targets are modelled as explicit network nodes. This strengthens conceptual coherence but narrows the evidence base and excludes related work using bibliometrics, structural equation models, governance networks or policy analysis without formal SDG representation. Screening and coding involved interpretive judgement even with a structured rubric, and some modelling nuances may not be fully captured. The analysis also focuses only on SDG interaction networks, not other sustainability domains where network science is applied, such as climate finance, supply-chain transitions or nature-based solutions. These boundaries introduce selection effects but clarify the analytical purpose, highlighting the need for broader comparative and cross-domain validation.

An Implementation-Grounded Multiplex Network Framework for SDG Analysis

Chapter 3 demonstrated that the majority of SDG network studies model interactions among goals, targets, and indicators while abstracting away from the actors, mechanisms, verification structures, and conditional constraints through which outcomes are actually produced. This omission results in what was termed an “implementation gap”: without a proper ontological grounding, networks may describe how goals relate conceptually, but they cannot evaluate whether specific outcomes are feasible, which pathways are blocked, or how design choices affect implementation possibilities.

This chapter responds directly to that gap by presenting the Four-Phase Implementation Network (4PIN) framework. The framework is explicitly ontologically and implementation-grounded, finance-conditioned, and verification-aware. It treats sustainable finance not simply as a funding mechanism but as an institutional environment that shapes which capabilities must be built, which outcomes must be demonstrated, and which forms of evidence are admissible for recognition and SDG attribution. This chapter establishes the design logic of the framework, specifies its ontology, presents its multiplex network architecture, and demonstrates the analytical capabilities that become available when implementation structures are represented explicitly rather than assumed.

The chapter proceeds as follows. Section 4.1 sets out the design requirements derived from the diagnostic analysis and sustainable finance realities. Section 4.2 introduces the framework at a conceptual level, including the Sustainable Value Creation Plan (SVCP) organizing logic and the procedural 4PIN method. Section 4.3 formalizes the ontological foundation that constrains what may be represented and how. Section 4.4 implements that ontology as a multiplex network with gates as traversal constraints. Section 4.5 presents the analytical affordances of the framework. Section 4.6 bridges to the empirical application that follows.

4.1 Design Requirements

4.1.1 Responding to the Implementation Gap

Chapter 3 established that existing SDG network models overwhelmingly treat the SDG agenda as a closed formal universe of goals, targets, and indicators, occasionally enriched by statistical relationships but rarely connected to implementation reality. As a result, these models cannot analyse whether outcomes are feasible under real constraints, where implementation may fail, or how institutional design influences attainable results.

An implementation-grounded framework must therefore do something fundamentally different.

It must:

- represent the structures through which implementation actually occurs;
- recognize that finance operates through conditional rules rather than neutral provision of capital;
- acknowledge that verification and recognition decisions determine which outcomes “count” in institutional systems; and
- preserve ontological distinctions that matter analytically, rather than collapsing everything into a single associative network.

In this chapter, these conditions are treated not as critique, but as explicit design requirements for model construction.

4.1.2 Requirements Derived from Sustainable Finance Practice

Sustainable finance does not merely “support” implementation; it structures it. Conditional finance creates binding requirements, timelines, verification demands, and adjudication points that shape what organisations must do and what evidence must exist for outcomes to be acknowledged. Institutional actors such as investors, regulators, auditors, certification bodies, and registry operators do not simply observe outcomes; they authorise or refuse recognition of outcomes.

To ground these realities in the framework, the sustainable finance argument previously developed in Chapter 2 is operationalised here as explicit design requirements.

Achieving the Sustainable Development Goals depends on mobilizing finance toward development priorities and translating commitments into verified outcomes. In operational terms, sustainable finance refers to financial arrangements that (i) mobilise capital toward sustainable development priorities and (ii) condition access to that capital, or its pricing, on requirements that must be satisfied at specific stages and demonstrated through defined evidence and verification processes (UN DESA, 2024). This framework analyses how contractual conditions and external adjudication structure pathways from financed obligations to verified outcomes and SDG attribution.

Covenants are binding clauses that condition capital access on verified compliance with specified sustainability requirements; if conditions are not met, pricing benefits or disbursements may be withheld (Auzepy et al., 2023).

An **NDPE** (No Deforestation, No Peat, No Exploitation) covenant illustrates this: it requires rejecting suppliers linked to recent deforestation, applying cut-off dates, and operating grievance procedures (Garrett et al., 2019). Implementation requires capabilities including geo-referenced supplier mapping, satellite screening, and case-handling processes.

Environmental and Social Action Plans (ESAPs) operationalise covenant requirements through time-bound, evidence-linked implementation programmes. Whereas covenants establish binding conditions; ESAPs operationalise those conditions through sequenced actions. While characteristic of development finance, analogous milestones appear in private-investment instruments such as KPI schedules or certification roadmaps.

The framework proposed in this study adopts a transaction-centered perspective where agency is represented exclusively through enforceable documentary artifacts, such as covenants, action plans, and verification decisions, rather than through modeled actor behavior or preferences (Flammer, 2021). In this transactional setting, “participants that provide finance” typically include lenders, bond investors, development finance institutions, blended-finance facilities, and commercial banks, while “participants that receive finance” include corporate borrowers, project-level entities (such as SPVs), and occasionally financial intermediaries. **Actors** therefore enter the model only through these artifacts. For example, an auditor appears through required verification, the audit report, and the resulting compliance decision. The practical implication being that, contrary to the artifacts (e.g., a covenant), an auditor may not be expressed explicitly as a network node. This choice avoids behavioural speculation and keeps the model anchored in auditable, institutionally consequential decisions.

Outcomes are verifiable operational states that result from implemented capabilities and can be independently verified. Examples include verified hectares of forest protected, documented hectares under restoration with confirmed survival rates, measured reductions in agrochemical use, or metered renewable energy volumes. Outcomes refer to observable operational conditions, including forest cover maintained, trees surviving, inputs reduced, electricity produced, rather than plans, certifications, or revenues. Outcomes exist independently of whether markets recognise them.

Capabilities, in this framework, refer to the organisational systems, procedures, and operational functions that make such outcomes possible in practice (for example, traceability systems, monitoring and reporting systems, farmer engagement and compliance management, restoration implementation capacity, or plant-level metering and data systems). They are not commitments or intentions, but built and implemented organisational capacities that repeatedly produce outcomes under verification.

Verification draws on documented capabilities and remote sensing, traceability systems, and third-party audits (Austin et al., 2021). For NDPE, verification relies on satellite monitoring, supplier traceability, and audit conclusions. If verification confirms no deforestation above thresholds, the outcome is verified and attributable to SDG targets (e.g., 15.1). If deforestation is detected or evidence incomplete, verification fails, blocking downstream SDG attribution, for example, where restoration or sourcing capabilities exist on paper but cannot demonstrate that all sourcing areas remain deforestation-free during the relevant period, the implementation effort exists but the operational outcome cannot be verified. Verification can operate as a financial gate, a pricing mechanism, or simply a disclosure requirement, depending on instrument design. In tranche-based, results-based, or covenant-conditional structures, failed verification can block disbursement, delay financing, or escalate toward default. In sustainability-linked instruments, failed verification typically adjusts pricing rather than access to capital. In weaker assurance regimes, verification may have no direct financial consequence at all, even if reputational or policy consequences remain. Once verified, outcomes can be attributed to firm-proximate SDG targets; recognition and revenue may follow but do not create the outcome.

Recognition refers to externally conferred decisions determining whether verified outcomes qualify for specific benefits, legitimacy, or continued program participation. Market recognition, such as chain-of-custody certification (Lambin et al., 2018), governs access to premiums or markets rather than outcome existence. Recognition determines benefit eligibility; it does not determine whether outcomes exist.

Monitoring, reporting, and verification (MRV) systems provide baselines, measurement procedures, reporting routines, and auditable records that support independent assurance and credible impact claims in sustainable finance and impact investing, increasingly relying on digital monitoring and traceable data logs (Simnett, 2012; Reeder et al., 2015; Ecklu and Thomas, 2025). In this framework, MRV is not a parallel informational activity but the evidentiary infrastructure that makes verification decisions possible. MRV systems generate the documented proof against which covenant compliance, eligibility conditions, and performance thresholds are assessed. Evidence generated through MRV is assessed by external authorities such as auditors, independent verifiers, or lenders' technical advisors, determining whether conditions are met. Where covenants or result-based conditions require demonstrable outcomes, MRV provides the auditable trail linking organisational capabilities to observable operational states. This means MRV functions as a gatekeeper: if evidence confirms compliance, verification can pass and unlock attribution, recognition, or subsequent financing tranches; if evidence is incomplete or contradictory, verification fails regardless of implementation effort. In this sense, MRV operationalises the relationship between contractual conditionality and outcome credibility, translating institutional commitments into verifiable claims.

4.1.3 Core Design Principles

On this basis, the framework adopts five core principles (CP).

1. **Finance is not causation**

Finance, implementation, outcomes, and recognition operate in different domains and must be represented separately.

2. **Conditionality must be explicit**

Covenants, eligibility rules, and action plan requirements must appear as structural constraints, not background narrative.

3. **Verification functions as a gate**

Outcomes do not advance to recognition unless evidence satisfies adjudication rules; therefore verification must be encoded as a binary decision point.

4. **Outcomes differ from value interpretations**

Operational outcomes are not themselves “impact.” Business value and societal value are interpretations layered upon verified operational states and must not be collapsed into them.

5. **Analysis must be pathway-based**

Feasibility, bottlenecks, and counterfactuals must be analysable as structural properties of pathways under gate constraints, not as statistical artefacts or expert interpretations alone.

The remainder of this chapter shows how these principles are embodied in the 4PIN framework.

4.2 Framework Overview

The Four-Phase Implementation Network (4PIN) framework provides a structured way to represent and analyse finance-enabled SDG implementation systems without collapsing fundamentally different processes into overly simplified goal-interaction structures. Whereas Chapter 3 demonstrated that most SDG network approaches treat goals, targets, and indicators as the primary analytical entities, the 4PIN framework is designed to represent the institutional, conditional, and verification structures through which outcomes come into being and are acknowledged.

To make this shift analytically credible, the framework must do three things explicitly: (i) preserve ontological distinctions between finance, implementation, evidence, recognition, and SDG attribution; (ii) embed conditionality and verification as structural rather than contextual elements; and (iii) enable pathway analysis under documented constraints rather than inferred or assumed causal interactions. The framework therefore integrates ontological precision, multiplex architectural design, and a traversal logic governed by evidence-dependent gates. These elements work together, rather than separately, to produce an implementation-grounded analytical instrument.

4.2.1 The SVCP Organising Logic

At the conceptual centre of the framework lies the Sustainable Value Creation Plan (SVCP). SVCPs articulate how conditional finance translates into capability investments, which generate operational outcomes, which may subsequently be interpreted as business or societal value, and, where admissible evidence exists, attributed to SDG targets. This structure provides the organising logic for how implementation is represented.

Sustainable Value Creation Plans (SVCPs) reflect an emerging private-markets perspective emphasising that sustainability should be embedded in value-creation logic across the investment lifecycle (PRI, 2025; Zaccone & Pedrini, 2020). SVCP is used strictly as an analytical integration layer that organises how sustainability conditions, implementation actions, verification processes, and value pathways are aligned over time; it does not prescribe behaviour nor replace covenants or ESAPs.

The 4PIN framework requires explicit domain logic that orders implementation activity before formal modeling. The SVCP provides this logic by distinguishing finance-imposed conditions, organizational capabilities built to meet those conditions, operational outcomes produced by those capabilities, and business and societal value interpretations of those outcomes (Höchstädter & Scheck, 2015).

The SVCP framing organizes implementation pathways across five layers and two sub-layers:

- **L1 (Finance):** Covenants and eligibility rules establishing binding requirements
- **L2 (Implementation):** Organizational capabilities (monitoring systems, traceability, grievance procedures)
- **L3 (Outcomes):** Verified operational results (hectares protected, restored, energy generated)
- **L3BV/L3SV (Value):** Business revenue and societal benefit interpretations
- **L4/L5 (SDG):** Firm-proximate targets and aggregated goals

The identification of these five main layers contributes to observing CP1.

Progression across these layers is not automatic. Movement from capabilities to outcomes, and from outcomes to recognised value or SDG attribution, is conditioned by verification and recognition decisions that act as **gates**. These gates are not outcomes themselves, but adjudications that determine whether pathway progression remains feasible.

Critical attribution rule: Only verified operational outcomes (L3) map to SDG targets (L4). Business-value and societal-value interpretations (L3BV, L3SV) are ex post assessments, not SDG contributors. This prevents conflation of operational outcomes with market recognition or revenue effects. The subdivision of L3 into sublayers L3BV/L3SV contributes to observing CP4.

External recognition decisions (assurance, certification, buyer eligibility, policy qualification) can open or block access to markets and capital. These appear as gates conditioning progression without being outcomes. Under an NDPE covenant, the operational outcome is deforestation-free sourcing within defined supply areas. Independent verification relies on satellite monitoring, traceability, and audit conclusions drawing on approaches discussed in empirical work on corporate deforestation commitments and supply-chain governance (Austin et al., 2021; Garrett et al., 2019). If verification confirms no deforestation above thresholds, the G2 gate passes; if deforestation is detected or evidence incomplete, G2 fails, blocking downstream SDG attribution despite implementation efforts.

Within 4PIN, verification and recognition decisions exist as real adjudications, but their constraining effects are represented as gate states on network edges, enabling gate-constrained reachability, minimal source-to-target cut sets, and counterfactual toggles under documented evidence using standard graph-theoretic concepts for paths and cuts (Newman, 2010) within a multilayer representation framework (Kivela et al., 2014).

The identification of different gate types and their association to functional capacities and their impact on reachability contribute to CP2 and CP3.

Figure 4 depicts SVCP elements, gate categories, and the SDG attribution rule: only verified operational outcomes (L3) map to firm-proximate SDG targets (L4). Business-value and societal-value nodes are interpretations, not direct SDG contributors.

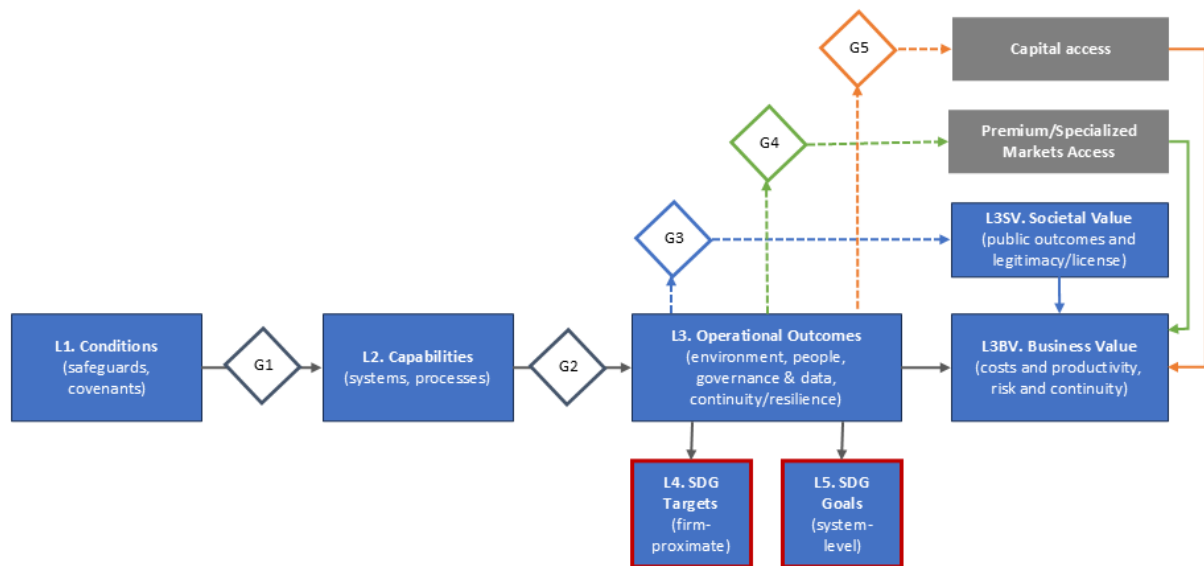


Figure 4. SVCP with Gates and SDG attribution. Only verified operational outcomes (L3) map to SDG targets (L4). Business and societal values are interpretations. Gates (G1 to G6) condition progression. Solid arrows: implementation effects; dashed arrows: recognition-dependent routes.

4.2.2 The 4PIN Method

The SVCP provides conceptual structure; the 4PIN procedural method provides methodological discipline for translating real systems into analyzable multiplex networks.

We apply the Four-Phase Implementation Network (4PIN) framework as a procedural method for constructing and analysing implementation-grounded networks. It follows design-science principles by treating the network representation and associated analytical procedures as a decision-support artifact (Hevner et al., 2004; Peffers et al., 2007), extending them to environmental sustainability contexts (vom Brocke et al., 2020).

4PIN proceeds through the four phases represented in Figure 1).

Framing defines the phenomenon under study, the analytical boundary, the time window, the unit of analysis, and the decision questions. **Abstraction** fixes the modeling grammar, including node classes, relation types, gate categories with admissible evidence, and the attribution rule that only verified operational outcomes may link to SDG targets. **Conceptualization** implements these abstractions as a layered directed network with explicit provenance, confidence fields, and external checks encoded as gate attributes with pass-or-fail states. **Analysis** evaluates the instantiated network using decision-oriented methods, including reachability under gate states, identification of minimal source-to-target cut sets, and counterfactual gate-state toggles that test how changes in covenants, verification, or eligibility alter feasible pathways (Newman, 2010).

The structure implies either-or routing. The same SDG target may be reachable through alternative verified outcomes, for example forest protection via deforestation-free procurement or via restoration progress, while gate logic governs which routes are open at a given time. This feature reflects established insights from resilience and systems theory that multiple pathways may exist to the same functional outcome, subject to constraints and thresholds (Lade et al., 2020; Walker et al., 2004).

4.2.3 Phase I Framing: system definition and research questions

The system under study is a sustainable-finance-conditioned SDG implementation pathway system, consisting of documented finance conditions, firm-internal capability investments, external verification and recognition processes, and rules governing SDG attribution.

The analytical boundary spans finance terms, implementation mechanisms, verification and recognition decisions, and SDG attribution. It excludes macroeconomic spillovers and policy interactions beyond firm-proximate, documentable pathways. The unit of analysis is a finance-gated implementation pathway, defined as a sequence from finance conditions through capability building to verified outcomes and their interpretations.

This framing treats SDG implementation as a constrained dynamic system: outcomes do not follow automatically from commitments but emerge only when capability investments traverse externally adjudicated verification and recognition processes. This makes finance conditionality and verification decisions part of the causal structure rather than contextual background.

Within this framed system, the study addresses three ontology-guided questions:

1. Can sustainable-finance documentation be translated into an analysable network with explicit coding rules, provenance, and confidence tags, without reducing contractual and verification complexity to simplified indicator mappings?
2. Which obligatory sequences and contingent routes arise once documented gates are applied, and how do these sequences structure feasible versus blocked implementation pathways?
3. Does a gate-aware network surface decision-relevant constraints that association-based SDG network mappings miss, particularly where attribution feasibility depends on verification outcomes rather than intent or correlation?

These questions align the framework explicitly with complexity-science reasoning: the system is path-dependent, rule-constrained, and adjudication-sensitive, and feasibility must therefore be analysed under the structural conditions imposed by finance and verification architectures rather than assumed from stated commitments.

4.3. Ontological Questions

4.3.1 Phase II Abstraction: ontology and modelling grammar

In the abstraction phase, the modelling grammar is fixed by declaring the ontological categories, relations, and constraints used to represent finance-enabled SDG implementation pathways. This step establishes the conceptual distinctions required for subsequent network construction, including the separation between finance instruments and imposed conditions, firm-internal capability investment commitments, action plans, operational capabilities, verified operational outcomes, adjudication processes, value interpretations, and SDG targets.

The ontological abstraction provides the domain logic that constrains what may be represented in the network and how elements may be linked. It encodes attribution rules, such as the requirement that only verified operational outcomes may contribute to SDG targets, and distinguishes between outcomes themselves and downstream recognition or value interpretation processes.

Existing semantic models relevant to sustainable finance and the SDGs largely develop along parallel tracks, with limited explicit treatment of finance-conditioned SDG implementation pathways. On the SDG side, [SDG Interface Ontology](#) (SDGIO) formalises SDG goals, targets, indicators, and their term semantics, while SDG-focused knowledge graphs such as [SustainGraph](#) structure SDG targets and associated progress information for tracking and integration (Fotopoulou et al., 2022; UNEP, 2024).

On the finance and sustainability side, ontology efforts such as the Sustainable Finance Information Requirement (SFIR) ontology and ESGOnt focus on structuring reporting and assessment concepts and enabling alignment between ESG information and SDG themes. These approaches primarily address disclosure, classification, and assessment semantics rather than implementation dependencies (Farghaly & Jones, 2023; Vijaya et al., 2025).

Domain-specific decision-support knowledge graphs are also emerging, for example, NatureKG proposes an ontology and instantiated knowledge graph tailored to nature finance, linking actions, evidence, and risk-relevant relationships (Kushwaha et al., 2025). In parallel, “investment pathway” framing is prominent in SDG finance policy and agenda-setting work, including the OECD-UNDP Framework for SDG Aligned Finance and the SDG “Six Transitions” investment pathways, yet these contributions are not formal ontologies and typically do not encode verifiable implementation dependencies from financed actions to outcomes to SDG target attribution (OECD, 2020; UNSDG, 2023).

The full ontological specification is provided in Annex 4 (also available at <http://w3id.org/fourpin>) and formalised in the Web Ontology Language (OWL) as a machine-readable artefact. Annex 4 documents the complete set of classes, object properties, and constraints, enabling inspection, reuse, and replication across cases. In the network representation used for analysis, verification and recognition decisions are treated as real adjudications in the domain, while their constraining effects are represented analytically as gate states on relations rather than as standalone nodes.

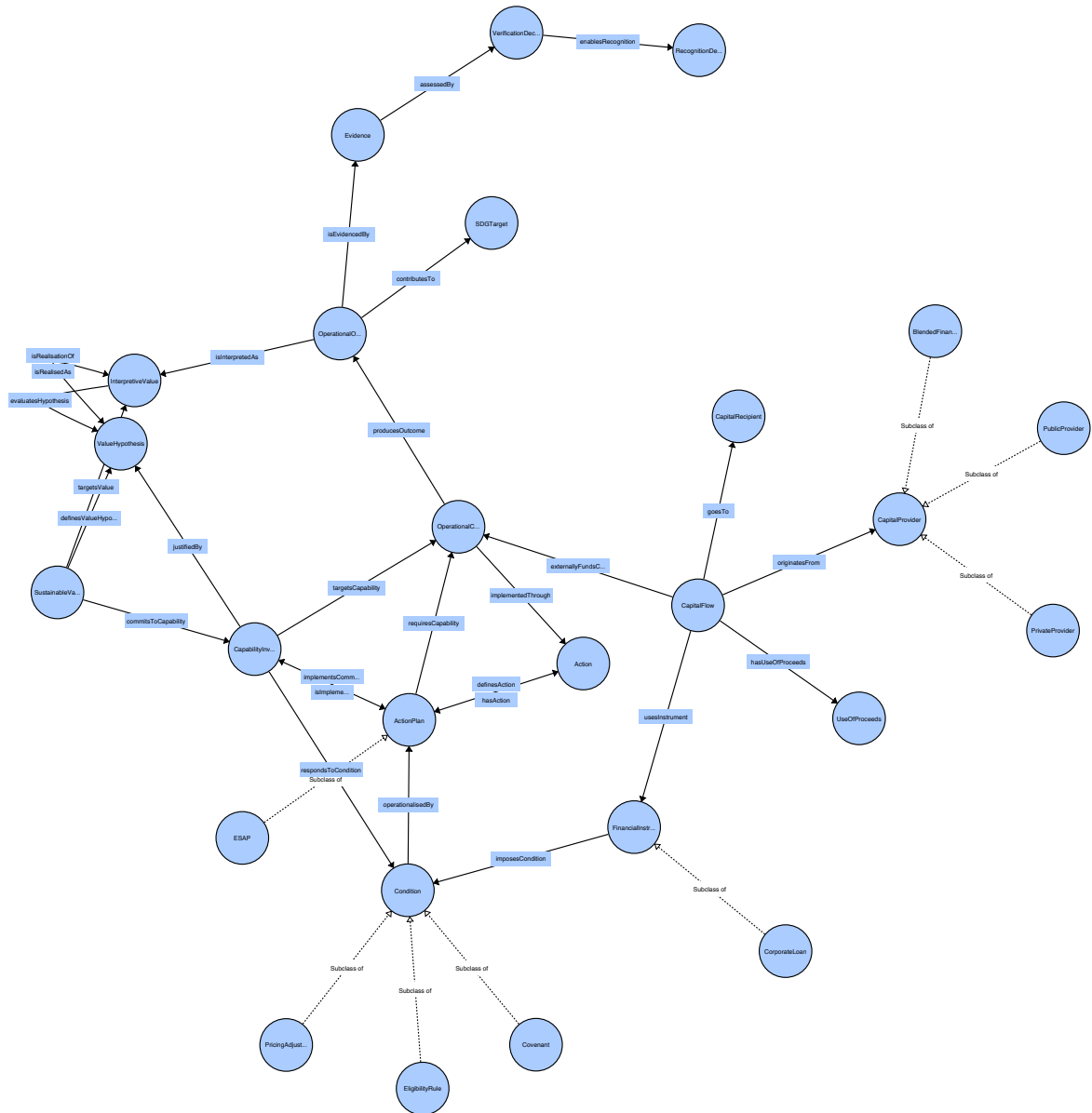


Figure 5. Ontological abstraction of the 4PIN domain (OWL). Core classes and relations defining finance-imposed conditions, capability investment commitments, action plans, verified outcomes, adjudication points, and SDG attribution constraints, fixed prior to network construction. Generated by [WebVOWL](https://w3id.org/fourpin) (Lohmann et al., 2016) and accessible at <http://w3id.org/fourpin> (generated using).

The ontology functions as a reusable abstraction layer. It does not prescribe substantive outcomes or causal claims; rather, it constrains what kinds of relations may be represented and how evidence, verification, and attribution are encoded. This separation ensures that domain assumptions are explicit and inspectable before network construction and analysis.

4.3.2 Core Ontological Classes

These ontological domains below map to the layered network structure as follows: Financial domain → L1, Conditionality and Implementation domains → L2, Outcome domain → L3, Interpretation

domain → L3BV/L3SV, Impact domain → L4/L5. The identification of these classes in the ontology enables 4PIN to meet Core Design Principles CP1 and CP4 (section 4.1.3).

A2.1 Financial domain

- **CapitalProvider:** An entity authorised to supply capital. Subclasses include:
 - PublicProvider
 - PrivateProvider
 - BlendedFinanceVehicle
- **CapitalRecipient:** An entity that receives capital, such as a firm, project, program, or special-purpose vehicle.
- **FinancialInstrument:** A contractual arrangement that defines the terms under which capital is provided. Examples include corporate loans, equity, guarantees, grants, bonds, and insurance.
- **CapitalFlow:** A time-bound transaction event associated with a financial instrument, such as disbursement, repayment, interest payment, or pricing adjustment.
- **UseOfProceeds:** A declared restriction on the application of a capital flow. This class may be absent in fungible corporate lending contexts.

A2.2 Conditionality and coordination domain

- **Condition:** A binding requirement attached to a financial instrument that constrains access to capital or its pricing. Subclasses include:
 - Covenant
 - EligibilityRule
 - PricingAdjustmentRule
- **SustainableValueCreationPlan (SVCP):** SustainableValueCreationPlan (SVCP): An analytical coordination framework used in this study to organize how sustainability-related conditions, implementation actions, verification processes, and value pathways are aligned over time within finance-enabled implementation pathways.
- SVCPs are not assumed to be formally documented instruments in all cases; rather, they provide an interpretive integration layer that allows coordination logic to be reconstructed analytically from documented covenants, action plans, and monitoring protocols. The SVCP framing distinguishes finance-imposed conditions, capability investment commitments, operational outcomes, and value interpretations without requiring a standalone plan document.
- In the FS case instantiation, SVCP logic is operationalized through the Environmental and Social Action Plan (ESAP), which translates covenant requirements into sequenced actions.

- **ValueHypothesis:** A firm-internal articulation of expected business value arising from compliance and capability development, such as risk reduction, market access, resilience, or cost-of-capital effects. Value hypotheses are ex ante expectations and do not themselves constitute realised value; they may be supported, partially supported, or contradicted by ex post value interpretations grounded in verified outcomes.
- **CapabilityInvestmentCommitment:** A firm-internal strategic and budgetary commitment to build or upgrade one or more operational capabilities in response to imposed conditions and guided by an SVCP-defined value hypothesis. This commitment precedes and enables downstream action planning.

The identification of these classes in the ontology enables 4PIN to meet Core Design Principle CP2 (section 4.1.3).

A2.3 Implementation domain

- **ActionPlan:** An operationalisation instrument that translates conditions and capability investment commitments into time-bound actions, responsibilities, deliverables, evidence requirements, and verification checkpoints. Environmental and Social Action Plans (ESAPs) are a common instance. Action plans operationalise contractually imposed conditions and translate SVCP-defined capability investment commitments into executable actions and evidence requirements.
- **Action:** A discrete implementation step defined within an action plan.
- **OperationalCapability:** An organisational capability required to implement actions and produce outcomes, such as monitoring systems, supplier traceability, grievance mechanisms, or compliance procedures.

The identification of these classes in the ontology enables 4PIN to meet Core Design Principle CP3 (section 4.1.3).

A2.4a Outcome, evidence, and decision domain

- **OperationalOutcome:** A verifiable operational state of the world resulting from implemented capabilities. Outcomes exist independently of their recognition or valuation.
- **Evidence:** Documented information that supports claims about the existence of an operational outcome. Examples include audit reports, satellite data, system logs, and inspection records.
- **VerificationDecision:** A determination by an authorised body that evaluates whether evidence demonstrates that specified conditions or outcome criteria have been met.
- **RecognitionDecision:** A determination that grants or withholds programmatic, market, or policy recognition, such as certification, eligibility, or access to premiums.

The identification of these classes in the ontology enables 4PIN to meet Core Design Principle CP3 (section 4.1.3).

A2.4b Gate (Adjudication Constraint)

Gate: A computational representation of an externally adjudicated decision point that conditions pathway traversal in the network model. Gates formalize the constraining effects of VerificationDecisions and RecognitionDecisions without duplicating those entities as network nodes.

- **Gate types** and their ontological grounding:
 - G1 (Readiness): Conditions imposed by FinancialInstrument or ActionPlan that must be satisfied before implementation proceeds
 - G2 (Outcome Verification): VerificationDecision determining whether OperationalOutcome meets admissible evidence requirements
 - G3 (Disclosure): RecognitionDecision governing disclosure acceptance or societal communication
 - G4 (Market Certification): RecognitionDecision granting market or program certification status
 - G5 (Registry Eligibility): RecognitionDecision determining eligibility for registries or capital programs
 - G6 (Legitimacy): RecognitionDecision reflecting stakeholder consent, grievance resolution, or social license determinations
- **Gate states:** Each gate carries a binary state (PASS/FAIL) based on documented evidence. When a gate state is FAIL, the corresponding network edge is not traversable during pathway analysis.
- **Ontological status:** Gates are analytical constructs derived from VerificationDecision and RecognitionDecision entities but represented as edge attributes in the network model rather than as standalone nodes.

The identification of these classes in the ontology enables 4PIN to meet Core Design Principle CP3 (section 4.1.3).

A2.5 Interpretation and impact domain

- **InterpretiveValue:** A business, financial, or societal interpretation of an operational outcome, such as revenue effects, risk reduction, or reputational benefit. Interpretive values are ex post interpretations of verified operational outcomes and can be used to evaluate the value hypotheses articulated ex ante in an SVCP.
- **SDGTarget:** A specific target under the United Nations Sustainable Development Goals.

Firm-proximate targets are those to which firm-level operational outcomes can be attributed through direct, mechanistically documented links, subject to the following criteria:

1. Causal directness: The outcome directly affects the target indicator without requiring intermediate transformations or spillover assumptions.
2. Spatial and temporal containment: The outcome occurs within the operational boundary of the finance-enabled pathway and the analytical time window.
3. Documented evidence chain: The outcome-to-target link is supported by verification evidence that explicitly addresses the target's indicator or sub-indicator.

Examples of firm-proximate targets in land-use contexts:

- SDG 15.1 (forest protection) via verified deforestation-free sourcing
- SDG 15.2 (sustainable forest management) via certified restoration
- SDG 7.2 (renewable energy) via metered biomass electricity generation

Non-proximate targets include those requiring:

- National-level aggregation (e.g., SDG 1.1 poverty reduction from employment effects)
- Indirect mechanisms (e.g., SDG 13.2 climate mitigation from avoided emissions)
- Spillover assumptions (e.g., SDG 8.4 resource efficiency from supply chain influence)

The firm-proximate distinction does not imply that non-proximate contributions are unimportant, only that they fall outside the analytical scope of direct, finance-conditioned pathway attribution. The identification of these classes in the ontology enables 4PIN to meet Core Design Principle CP4 (section 4.1.3).

4.3.3 Ontological Relations

The ontology defines the following primary object properties.

Financial relations:

- `originatesFrom` (CapitalFlow → CapitalProvider)
- `goesTo` (CapitalFlow → CapitalRecipient)
- `usesInstrument` (CapitalFlow → FinancialInstrument)
- `hasUseOfProceeds` (CapitalFlow → UseOfProceeds) (optional)

Conditionality and coordination

- `imposesCondition` (FinancialInstrument → Condition)
- `definesValueHypothesis` (SVCP → ValueHypothesis)
- `commitsToCapability` (SVCP → CapabilityInvestmentCommitment)

- `respondsToCondition` (CapabilityInvestmentCommitment → Condition)
- `justifiedBy` (CapabilityInvestmentCommitment → ValueHypothesis)
- `targetsCapability` (CapabilityInvestmentCommitment → OperationalCapability)

Implementation

- `operationalisedBy` (Condition → ActionPlan)
- `implementsCommitment` (ActionPlan → CapabilityInvestmentCommitment)
- `isImplementedByPlan` (CapabilityInvestmentCommitment → ActionPlan)
- `definesAction` (ActionPlan → Action)
- `requiresCapability` (ActionPlan → OperationalCapability)
- `implementedThrough` (OperationalCapability → Action)

Outcomes and decisions

- `producesOutcome` (OperationalCapability → OperationalOutcome)
- `isEvidencedBy` (OperationalOutcome → Evidence)
- `assessedBy` (Evidence → VerificationDecision)
- `enablesRecognition` (VerificationDecision → RecognitionDecision)

Interpretation and attribution

- `isInterpretedAs` (OperationalOutcome → InterpretiveValue)
- `contributesTo` (OperationalOutcome → SDGTarget)
- `evaluatesHypothesis` (InterpretiveValue → ValueHypothesis)
- `targetsValue` (SVCP → InterpretiveValue)

Optional relation for public or DFI contexts:

- `externallyFundsCapabilityBuild` (CapitalFlow → OperationalCapability)

4.3.4 Ontological Constraints

The following constraints apply:

1. CapitalFlow is disjoint from OperationalOutcome.
2. FinancialInstrument does not produce OperationalOutcome.
3. CapabilityInvestmentCommitment is disjoint from CapitalFlow.
4. RecognitionDecision is disjoint from VerificationDecision.

5. Attribution constraint: Only OperationalOutcome for which there exists a VerificationDecision with state=PASS may contributeTo SDGTarget.
6. OperationalOutcome existence is independent of RecognitionDecision, which may grant or withhold market access without creating or destroying the outcome.
7. UseOfProceeds may be absent in corporate lending contexts.

These constraints prevent conflation between finance, implementation, and impact, thus contributing to meet Core Design Principle CP1 (section 4.1.3).

4.4 Multiplex Architecture

4.4.1 Phase III Conceptualisation: Network Representation

Conceptualization implements the abstract ontology as a directed network representation. Distinct types of relations are organized on separate analytical layers in order to preserve the ontologically defined separation between finance conditions, implementation dependencies, verification and recognition processes, and SDG attribution (Boccaletti et al., 2014; Kivela et al., 2014).

Following the SVCP framework (Section 2.8), the network is structured across seven analytical layers (Table 3) to preserve separation between finance conditions, implementation, verified outcomes, value interpretations, and SDG attribution while retaining documented interdependencies. The explicit identification of these layers enables 4PIN to meet Core Design Principle CP1 (section 4.1.3).

Nodes represent the substantive elements through which implementation pathways progress. These include finance-imposed conditions, organizational capabilities, verified operational outcomes, value interpretations, and SDG targets and goals. In line with the attribution rule defined at the abstraction stage, only verified operational outcomes connect directly to SDG targets, and each Outcome-to-Target relation carries an explicit mapping note and evidence anchor. The explicit identification of conditions as nodes enables 4PIN to meet Core Design Principle CP2 (section 4.1.3).

Edges encode functional relationships between nodes, such as implementation effects, recognition-dependent routes, value interpretation links, and aggregation. Edges typically connect nodes across adjacent layers ($L1 \rightarrow L2$, $L2 \rightarrow L3$, $L3 \rightarrow L4$), though cross-layer or within-layer edges are permitted where documented dependencies exist. Externally adjudicated verification and recognition decisions are not modelled as nodes but are implemented as gate attributes on edges. A gate records whether the required evidence has been accepted or rejected by the relevant authority. When a gate fails, the corresponding relation is not traversable. Gates do not contribute to degree or centrality; they operate solely as constraints on pathway traversal.

The explicit identification of conditions on edges conditioning the traversal of the graph enables 4PIN to meet Core Design Principle CP3 (section 4.1.3). The explicit identification of conditions on edges conditioning the traversal of the graph enables 4PIN to meet Core Design Principle CP3 (section 4.1.3).

The representation preserves a clear analytical separation between implementation, verification, recognition, and attribution, while allowing their interaction to be examined through auditable, rule-based constraints. The ontology specified in Annex 4 defines the full set of admissible entities and relations. The network representation selectively visualises only those elements that constitute pathway progression points, consistent with established multilayer network representation practice in which only a subset of ontological elements is instantiated as node-layer tuples for analysis (Kivela et al., 2014), in order to support computational analysis without conflating planning constructs, contextual actors, or adjudication logic with realised system states.. The full ontology can be visualized and analysed at <http://w3id.org/fourpin> .

Table 3 summarises how ontological elements are represented in the network and clarifies the analytical role each representation plays.

Table 3. Ontology-to-network representation mapping.

Ontological element	Network representation	Analytical role
Condition (Covenant)	Node (L1)	Finance-imposed requirements
OperationalCapability	Node (L2)	Implemented organisational capacity
OperationalOutcome	Node (L3)	Verified pathway progression
InterpretiveValue (Business/Societal)	Node (L3BV / L3SV)	Ex post value interpretation
SDGTarget / SDGGoal	Node (L4 / L5)	Attribution endpoints
Ontological relations (e.g. enables, produces, contributesTo)	Directed edge (typed, layered)	Functional dependency and pathway progression
VerificationDecision	Gate attribute (G2)	Conditions Outcome → Target traversal
RecognitionDecision	Gate attributes (G3–G6)	Conditions value and revenue routes
ActionPlan (ESAP)	Embedded in edges	Operationalisation of conditions
CapabilityInvestmentCommitment	Implicit	Focus on realised capacities
ValueHypothesis	Not represented	Pre investment planning construct
Actors / FinancialInstrument	Contextual	Case framing, not pathway nodes

4.4.2 Seven-Layer Architecture

The multiplex network is organized across seven analytical layers (i.e. 5 main layers and two sub-layers) to preserve ontological separation while enabling integrated pathway analysis:

Layer 1 (L1) Finance and Conditionality: Contains finance-imposed conditions including covenants and eligibility rules that establish binding requirements. Nodes represent contractual obligations that must be satisfied for capital access, pricing benefits, or continued eligibility.

Layer 2 (L2) Implementation and Capabilities: Contains organizational capabilities that must be built to satisfy finance conditions and produce operational outcomes. Examples include supplier traceability systems, geospatial monitoring infrastructure, grievance mechanisms, and quality assurance processes.

Layer 3 (L3) Operational Outcomes: Contains verified operational outcomes produced through implemented capabilities. These represent observable operational states (i.e. hectares protected, trees surviving, emissions reduced, energy generated) that can be independently verified and attributed to SDG targets.

Layer 3BV Business Value: Contains ex post interpretations of operational outcomes from business perspective, including revenue streams, cost savings, risk mitigation, and market access benefits. These are value interpretations, not operational outcomes.

Layer 3SV Societal Value: Contains ex post interpretations of operational outcomes from societal perspective, including community benefits, ecosystem services, public health improvements. Like business value, these are interpretations of outcomes, not the outcomes themselves.

Layer 4 (L4) SDG Targets: Contains firm-proximate SDG targets to which verified operational outcomes can be attributed. Attribution follows the critical rule: only verified outcomes from L3 may link to L4 targets.

Layer 5 (L5) SDG Goals: Contains the 17 SDG goals to which targets aggregate. This layer enables goal-level analysis while preserving target-level specificity. This layered architecture prevents conflation of fundamentally different relationship types while enabling analysis of their interaction through cross-layer dependencies.

4.4.3 Gate Implementation

Gates operationalize verification and recognition decisions as binding constraints on pathway traversal. Five gate types (G1–G5) operate as institutionally adjudicated decision points with explicit evidence rules, defined adjudicators, and binary consequences for pathway feasibility. A sixth gate type (G6) acknowledges societal legitimacy adjudication, which is conceptually critical but structurally

distinct. Gates transform the network from a descriptive graph into a feasibility model. A pathway exists only if it can be traversed under current evidence and adjudication states.

Together, these condition progression at different decision moments:

G1 (Readiness Gate): Conditions imposed by financial instruments or action plans that must be satisfied before implementation proceeds. Examples: baseline assessments completed, monitoring systems operational, training delivered.

G2 (Outcome Verification Gate): Verification decisions determining whether operational outcomes meet admissible evidence requirements for SDG attribution. This is the critical gate for attribution, G2 failure blocks outcome-to-target linkage regardless of implementation effort.

G3 (Disclosure Gate): Recognition decisions governing disclosure acceptance or societal communication. Examples: sustainability report acceptance, public disclosure approval, stakeholder communication validation.

G4 (Market Certification Gate): Recognition decisions granting market or program certification status. Examples: FSC certification, Fair Trade approval, Roundtable on Sustainable Palm Oil membership.

G5 (Registry Eligibility Gate): Recognition decisions determining eligibility for registries or capital programs. Examples: carbon credit registry acceptance, green bond eligibility, impact investment inclusion.

G6 (Legitimacy Gate): Societal adjudication of acceptability through grievance resolution, stakeholder consent processes, and community legitimacy. Unlike G1 - G5, G6 is not universally formalised as a binary procedural decision point with a defined adjudicating authority. Its expression varies across contexts and may be continuous, negotiated, or iterative rather than discretely adjudicated. For this reason, G6 is recognised conceptually within the framework, but only instantiated as a gate where documentary evidence demonstrates structured decision authority and pathway-blocking effect.

Each gate carries a binary PASS/FAIL state when formally instantiated and evidenced. Where a gate fails, the corresponding pathway is not traversable. Gates do not contribute to network metrics (such as centrality); they function purely as traversal constraints. This implementation distinguishes planning (gates may exist conceptually) from realised pathway feasibility (gates must be demonstrably passed to enable progression). Accordingly, the canonical architecture visualises G1-G5, while G6 is instantiated only where legitimacy processes function as structured, adjudicated constraints.

This distinction between design and realization is essential: many SDG initiatives fail not because pathways do not exist conceptually, but because they cannot be traversed under binding verification and recognition requirements.

4.5 Analytical Affordances

With the architecture established, analysis no longer concerns whether goals are statistically associated, but whether outcomes are reachable under the documented conditions that govern implementation. Instead of describing interaction patterns, the framework assesses which outcomes are actually reachable under real implementation constraints..

4.5.1 Phase IV Network Model: Instantiation and Analysis

The final phase of the 4PIN method concerns network instantiation and analysis. In this study, instantiation is carried out using the Fueling Sustainability (FS) case. The analytical results derived from the instantiated network are reported in Section 5 (Results). This subsection therefore provides an overview of the analytical procedures as part of the methodological design, without reference to case-specific findings. The analytical procedures and graph theory tools used are inlined with the Core Design Principle defined in section 4.1.3.

Once the network is instantiated from documentary materials in accordance with the ontology and modelling grammar defined in Section 4.3, analysis proceeds in four steps. First, pathway tracing enumerates all directed sequences from finance-imposed conditions to operational outcomes and SDG targets, recording the associated gate sequences and evidence chains. Second, gate-state reachability analysis toggles individual gates to determine which outcomes and targets remain reachable under different adjudication states. Third, bottleneck analysis identifies minimal source-to-target cut sets, revealing the smallest combinations of gates whose failure would block access to selected outcomes or targets. Fourth, counterfactual tests selectively set specific gates to fail while holding the evidence graph constant, allowing necessary conditions to be distinguished from contributory ones.

All analyses operate on the instantiated network while preserving the declared modelling grammar, attribution rules, and evidence constraints. Algorithms, parameter settings, and intermediate outputs are documented in Annex 3 to enable transparency and replication.

4.5.2 Pathway Feasibility Analysis

The multiplex architecture with gate-conditioned traversal enables three analytical capabilities absent from standard SDG network approaches:

1. Reachability Analysis Under Constraints

Standard network analysis asks: "Is node B reachable from node A?" Gate-conditioned analysis asks: "Is node B reachable from node A given current gate states?" This distinction matters when verification or recognition failures block pathways despite implementation completion.

Reachability analysis proceeds through directed path enumeration from finance conditions (L1) through capabilities (L2) and outcomes (L3) to SDG targets (L4), recording gate sequences along each path. A pathway is feasible only if all gates along the path are in PASS state. This reveals which SDG targets are reachable under documented evidence and adjudication states, a question standard approaches cannot address.

This explicitly aligns with complexity reasoning, where feasibility depends not only on existence of components but on whether they can be activated in valid sequences under constraint.

2. Bottleneck Identification

Minimal cut set analysis identifies the smallest combinations of gates whose failure would block access to specific outcomes or targets. This reveals critical decision points where verification or recognition failures create systemic blockages.

For instance, if G2 (outcome verification) appears in all pathways to a target, then G2 is a necessary gate, its failure makes the target unreachable regardless of implementation effort. If G4 (market certification) appears in some but not all pathways, it is contributory but not necessary. Bottleneck analysis thus distinguishes binding constraints from optional enhancements.

This shifts discussion of “implementation barriers” from rhetorical claims to structurally demonstrable constraints.

3. Counterfactual Design Evaluation

Gate-state toggles enable counterfactual analysis: "How would outcomes change if verification standards were strengthened (more gates set to FAIL)? If compliance timelines were extended (more gates set to PASS)? If certification requirements were added or removed?" Unlike econometric counterfactuals, no causal assumptions are required: counterfactual analysis here concerns institutional design logic rather than statistical inference.

This supports ex ante stress-testing of covenant and verification designs before implementation, revealing which design choices create critical vulnerabilities and which provide redundant pathways. Unlike impact evaluation, counterfactual gate analysis requires no causal identification assumptions, it examines logical implications of documented conditions and adjudication rules.

4.5.3 Comparison with Standard SDG Network Approaches

Table 4 provides a comparison on how different analytical questions are addressed (or not) by the standard SDG network approaches described in chapter 3 and by the proposed framework (4PIN).

Table 4. Comparison between standard SDG network approaches and 4PIN

Analytical Question	Standard SDG Network Approaches (Tier A/B)	4PIN Implementation-Grounded Framework (Tier C)
Can outcome X be achieved?	Correlation-based inference: X co-varies with Y	Feasibility reasoning: Are all required gates in PASS state?
Where do pathways stall?	Not addressable	Bottleneck identification: Which gates block access to outcomes or targets?
How would design changes affect outcomes?	Not addressable	Counterfactual analysis: Toggle gate states and observe reachability effects
What causes indicator movement?	Correlation analysis or expert interpretation	Not claimed; focuses on documented constraints and evidentiary structure
How do goals interact?	Correlation, semantic co-occurrence, or expert scoring	Not primary focus; emphasis on implementation mechanisms rather than goal semantics
Who are implementation actors?	Not represented	Implicitly represented through documentary artifacts and capability structures
What verification is required?	Not represented	Explicitly represented as gate-conditioned dependencies and adjudication structures

The comparison reveals complementarity rather than substitution. Standard SDG network approaches are well suited to examining global interaction structures and cross-national patterns. The 4PIN framework, by contrast, is designed to diagnose implementation feasibility, identify bottlenecks, and evaluate design alternatives within documented finance-enabled pathways. Together, they address different analytical needs and decision contexts.

4.6 Empirical Application of the Implementation-Grounded Multiplex Framework

The preceding sections established the 4PIN framework's design requirements, ontological foundations, multiplex architecture, and analytical capabilities. Sections 4.1 through 4.5 defined what the framework represents and how it operates as an analytical instrument. The current section aims to demonstrate that the framework can be operationalized using real documentary evidence and that it generates decision-relevant insights that standard SDG network approaches cannot surface.

The empirical application examines a sustainable finance transaction involving Fueling Sustainability (FS), a Brazilian corn-ethanol producer, financed through an &Green facility. &Green is a blended-finance debt fund, structured as a private debt evergreen vehicle, that invests in commercial agricultural supply chains in tropical forest jurisdictions in order to decouple commodity production from deforestation while promoting socially inclusive land-use transitions. The facility is structured as a corporate loan containing sustainability-related covenants covering conservation, restoration, intensification, and Indigenous Peoples requirements. These covenant obligations are implemented through an Environmental and Social Action Plan (ESAP) that specifies time-bound actions, deliverables, admissible evidence, and verification checkpoints. The documentary corpus spans May 2022 to December 2025 and includes &Green governance documents, the ESAP and related contractual materials, third-party verification outputs, public sustainability disclosures, and certification records. Only evidence available in this corpus is used for network construction, gate-state assignment, and analysis.

The analysis proceeds in four steps. Section 4.6.1 establishes the case context and defines the evidentiary basis. Section 4.6.2 demonstrates network instantiation from documents, including confidence tagging and gate-state coding. Section 4.6.3 traces pathways from finance conditions through capabilities to verified outcomes, identifying bottlenecks and alternative routes. Section 4.6.4 applies counterfactual gate-state analysis to test how covenant and verification design choices affect pathway feasibility, demonstrating the decision-support capabilities outlined in Section 4.5.

4.6.1 Case Context and Documentary Evidence

The empirical material used in this study originates from a single sustainable-finance transaction involving Fueling Sustainability (FS), a Brazilian corn-ethanol producer, supported by an &Green facility. The case is used to instantiate and demonstrate the 4PIN method; it is not selected for causal inference.

FS was chosen because the transaction is well documented across the full sequence that the framework is designed to model: finance terms and covenants, implementation instruments, externally adjudicated verification and recognition processes, and documented operational outcomes. The case includes multiple third-party checks with non-trivial rejection risk, making it suitable for gate-based analysis.

The analytical boundary spans the period from May 2022 to December 2025 and includes finance conditions, implementation mechanisms, verification and recognition decisions, and SDG-relevant outcome attribution. Broader market dynamics, macroeconomic spillovers, and indirect policy effects are outside scope.

FS received an &Green facility in 2022 structured as a corporate loan with sustainability-related covenants. The facility embeds conservation, restoration, intensification, and Indigenous Peoples (IP) covenants that condition continued capital access on documented compliance. The loan is fungible corporate financing; there are no use-of-proceeds restrictions.

In the transaction, covenant requirements are operationalised through an **Environmental and Social Action Plan (ESAP)**. The ESAP specifies time-bound actions, responsibilities, deliverables, admissible evidence, and verification checkpoints through which covenant obligations are implemented. In analytical terms, the ESAP operationalises SVCP logic: the alignment of covenant requirements with firm-internal capability investments and value pathways over time.

Within the ontology and network model, the ESAP is treated as an **ActionPlan** that executes firm-internal capability investment commitments derived from the Sustainable Value Creation Plan (SVCP) logic. The ESAP does not redefine covenant obligations; it provides the executable specification that makes them implementable and verifiable.

The materials corpus comprises 10 publicly accessible or available-upon-request documents published between 2019 and 2025, selected for direct relevance to modeled elements, traceable provenance, and authoritative source status. This limited corpus is sufficient because key documents consolidate multiple evidence types: the ESAP operationalizes covenant requirements and capability targets; the 2024 third-party verification report verifies all operational outcomes; the FS sustainability report documents self-reported outcomes and CBIO revenues; and the ISCC Certificate Database provides certification records. Table 5 summarizes the corpus. Annex 3 provides evidence registers with persistent identifiers and page-level anchors linking these documents to all network nodes, edges, and gate assignments.

Table 5. Document corpus for the FS case

Document category	Number of documents
&Green governance and MRV framework	3
Third-party verification report	1
FS, &Green sustainability reports	2
ISCC certification system	3
RenovaBio carbon credit framework	1
<i>Total</i>	<i>10</i>

4.6.2 Evidence Handling and Network Instantiation

Each document is treated as raw network material. Nodes and relations instantiated from the corpus cite at least one source document and carry a confidence tag. A three-level confidence scheme is applied:

- **High:** Evidence from authoritative sources, such as facility agreements, audit reports, or regulatory texts, with explicit statements of condition satisfaction or outcome achievement.
- **Medium:** Evidence from credible secondary sources, such as sustainability reports or certification databases, where the link is mechanistically justified by standards or statutes but not explicitly verified in available documents.
- **Low:** Inferred from indirect indicators or stakeholder statements without independent verification. These links are excluded from the base network and used only in sensitivity analysis.

The thesis' author practitioner role provides process insight but introduces a risk of confirmation bias. To mitigate this, all modeled elements rely exclusively on publicly accessible documents, and low-confidence links are excluded from the main analysis. The full evidence register, coding dictionary, and admissible layer-by-relation pairs are provided in Annex 3 to enable independent reconstruction.

The documentary corpus provides the empirical basis for instantiating the abstract ontology and network representation defined in Chapter 3. Materials are not analysed directly in this section; they are used to populate nodes, relations, gate states, and evidence fields in the network. The resulting instantiated network is presented and analysed in Section 5.

Applying the 4PIN method to the FS case results in a finance-gated, evidence-tagged implementation network that links covenants to operational capabilities, verified outcomes, value interpretations, and firm-proximate SDG targets. The results are presented as analytical diagnostics of pathway feasibility.

The instantiated network contains **33 nodes and 41 edges** distributed across five analytical layers: finance and conditionality, implementation, operational outcomes, value interpretations (business and societal), and SDG targets and goals. Nodes are typed according to the declared ontology, and edges are typed according to admissible relation categories. Gate attributes (G1-G6) are assigned to edges where external adjudication is required. Table 6 summarises the node inventory by layer.

Table 6. Node inventory by layer.

Layer	Node type	Count	Examples
L1 Finance	Covenants	4	Conservation, restoration, intensification, IP

L2 Implementation	Capabilities	6	NDPE strategy, NDPE farmer engagement, restoration and intensification program capabilities, MRV and plant metering
L3 Outcomes	Operational outcomes	9	NDPE farms, forests protected, volume NDPE sourcing, restoration progress, farmers included via restoration, intensified degraded areas, verified biomass sourcing, on-site electricity, purchases compliant with IP policy
L3SV SocietalValue	Interpretations	3	Resilient farmers, forest condition improved, legitimacy or license
L3BV BusinessValue	Interpretations	4	SAF premium revenue, CBIO revenue, continuity or risk reduction, process energy reliability
L4 Targets	SDG targets	5	15.1, 15.2, 15.3, 15.5, 7.2
L5 SDGs	Goals	2	SDG 15, SDG 7

The network structure reflects four covenant-driven implementation streams: conservation, restoration, intensification and energy, and Indigenous Peoples safeguards. All streams originate in finance-imposed conditions and converge downstream through shared capabilities and verification processes.

Figure 6 presents the instantiated FS network produced by applying the 4PIN method and the data model defined in Chapter 4 and Annex 3 to the FS case documentation.

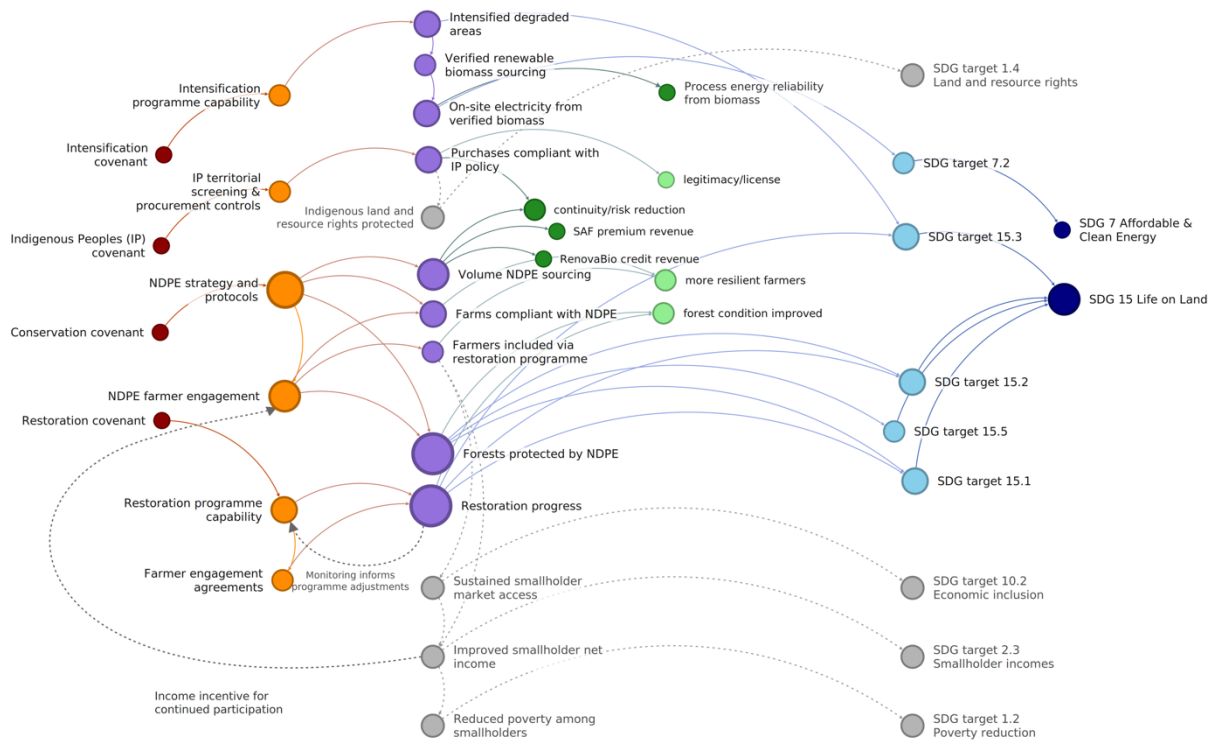


Figure 6. FS network graph: finance-gated pathways from covenants through capabilities to outcomes, value interpretations, and SDG targets. Solid coloured edges represent implementation dependencies, ungated value interpretations, SDG attribution and aggregation; dashed coloured edges represent recognition-dependent value routes. Gate attributes G1 to G6 sit on adjudicated edges. Grey nodes and solid grey edges indicate potential pathways not established by the case evidence: sustained smallholder market access (10.2), improved smallholder net income (2.3), reduced poverty among smallholders (1.2), and protection of Indigenous land and resource rights (1.4). Labelled dotted dark-grey return arrows illustrate possible feedback through income incentives for continued farmer participation and restoration monitoring informing programme adjustments. Potential pathways and feedback loops are illustrative and excluded from the reported network counts and analyses.

4.6.3 Pathway Analysis and Bottlenecks

Pathway tracing enumerates all directed sequences from finance entry points to operational outcomes and SDG targets under documented gate states. In the FS network, every feasible pathway from finance to SDG targets passes through a readiness gate (G1) and an outcome-verification gate (G2). Covenants do not connect directly to outcomes. Instead, they route through ESAP-defined actions and operational capabilities, such as supplier traceability, geospatial monitoring, grievance handling, restoration programme management, and biomass metering. These capabilities, once implemented, produce independently verifiable operational outcomes.

The results indicate that multiple pathways exist from finance conditions to the same SDG target. For example, SDG target 15.1 (terrestrial ecosystem protection) is reachable through verified deforestation-free sourcing outcomes or through verified restoration progress. These routes are represented as parallel Outcome-to-Target edges, each with its own evidence chain and gate sequence.

The instantiated network separates public accountability routes from private value-capture routes downstream of shared operational outcomes.

On the **public pathway**, only verified operational outcomes contribute to SDG targets. Attribution is governed exclusively by outcome-verification gates (G2) and remains unaffected by certification or registry failures.

On the **private pathway**, additional recognition and eligibility gates govern access to revenues. Certification audits, buyer eligibility decisions, and registry acceptance control access to sustainable aviation fuel (SAF) premiums, RenovaBio CBIO revenues, and continuity risk reduction. These recognition-dependent edges are distinct from Outcome-to-Target links and do not create operational outcomes.

This keeps SDG attribution to remain stable even when market recognition fails, while still making revenue dependence on certification and registry processes explicit.

Minimal source-to-target cut-set analysis identifies the smallest sets of gates whose failure would block reachability to selected targets or value nodes.

For land-related targets (SDG 15.1, 15.2, and 15.3), G2 outcome verification appears in every minimal cut set², indicating that verification throughput is a binding constraint. Readiness gates (G1) are necessary upstream but never sufficient on their own.

For SDG 7.2 (renewable energy), the minimal cut set includes outcome verification of verified biomass sourcing and plant metering, reflecting statutory requirements for attribution. Where revenue realization is considered, registry acceptance (G5) becomes decisive.

Recognition gates (G4 and G5) are decisive for revenue nodes but do not alter Outcome-to-Target reachability. Legitimacy-related gates (G6) control societal interpretations and operational continuity but do not create or remove SDG attribution links. Table 7 reports minimal cut sets for selected targets and revenue nodes.

Table 7. Minimal cut sets for key SDG targets and revenue nodes.

SDG or node	Minimal cut set	Interpretation
15.1	{G1, G2}	Readiness plus verification are necessary and sufficient
15.2	{G1, G2}	Same as 15.1 via restoration
15.3	{G1, G2}	Same as 15.1 via intensification
15.5	{G1, G2, G3}	Biodiversity condition requires societal communication where specified
7.2	{G1, G2}	Metering and verification drive attribution
SAF revenue	{G1, G2, G4, G5}	Readiness, verification, certification, registry acceptance
CBIO revenue	{G1, G2, G5}	Registry eligibility decisive

² Gate assignments follow G1 (readiness) conditions covenant-to-capability links; G2 (outcome verification) conditions capability-to-outcome links; G3-G6 condition value-interpretation and recognition routes (disclosure, certification, registry verification, and legitimacy). Full gate assignments, evidence anchors, and confidence levels are provided in the network data file (Supplement).

The network encodes either-or logic for SDG reachability. Targets can be reached through alternative verified outcomes rather than bundled achievements.

For SDG 15.1, reachability can proceed via forests protected by deforestation-free sourcing or via restoration progress. For SDG 15.2, restoration progress or verified NDPE-compliant farms can suffice, subject to mapping notes and evidence anchors. These alternatives are evaluated independently under identical gate-state and cut-set procedures.

This structure makes substitution effects explicit and prevents double counting of outcomes while preserving traceability of evidence.

4.6.4 Counterfactual Analysis and Decision Implications

Counterfactual analyses test sensitivity to specific gate failures while holding the evidence graph constant.

Setting G2 (outcome verification) to fail collapses reachability to all land-related SDG targets, even when covenants, plans, and capabilities remain in place. Disabling G4 or G5 removes SAF premiums and CBIO revenues while leaving Outcome-to-Target links intact. Removing G6 weakens legitimacy and continuity-related interpretations without affecting SDG attribution.

These counterfactuals separate feasibility of outcomes from conditions for value capture and confirm the analytical distinction between verification, recognition, and attribution.

Three results are robust across analyses. First, outcome verification is the dominant constraint for SDG reachability in the FS case. Second, recognition and registry processes bind revenue realization but not SDG attribution. Third, multiple verified outcome routes can satisfy the same target, allowing sequencing and substitution decisions to be made explicitly rather than implicitly.

Conclusion and Future Research

This thesis addressed a fundamental gap in SDG network science: existing approaches model interactions among goals, targets, and indicators while systematically abstracting away from the implementation mechanisms, finance conditions, and verification processes through which outcomes are actually produced. This abstraction limits analytical capacity to answer feasibility questions, diagnose bottlenecks, or evaluate institutional design choices, precisely the questions that matter for implementation.

The thesis responded through two integrated contributions. First, a systematic diagnostic framework (Chapter 3) revealing that 96% of SDG network studies model only formal goal structures without representing actors, processes, or mechanisms. Second, the Four-Phase Implementation Network (4PIN) framework (Chapter 4) providing an ontology-based, gate-conditioned multiplex architecture that explicitly represents finance conditions, capability dependencies, verification gates, and SDG attribution and demonstrates that these elements can be represented rigorously and consistently using available evidence.

This concluding chapter synthesizes contributions SDG governance and implementation research, sustainable finance practice, and network science methodology (Sections 5.1-5.3), addresses limitations and extensions (Section 5.4), and offers closing reflections (Section 5.5).

5.1 Contribution to Network Science

5.1.1 Methodological Innovation: Ontology-Driven Network Design

Network science provides powerful tools for analyzing complex systems, but applying these tools to sustainability challenges requires careful translation of domain phenomena into network structures. This thesis demonstrated that methodological choices made during system framing and network abstraction fundamentally constrain what analyses can reveal.

The diagnostic framework (Chapter 3) operationalized (Brandes et al., 2013) dual-theory approach, linking domain-specific knowledge with mathematical network theory into an eight-step evaluative instrument. Applied to 25 SDG network studies, the framework revealed systematic patterns: between 62% and 88% of studies adopt Tier A approaches (descriptive, UN Agenda-focused), between 12% and 36% adopt Tier B (intermediate, statistical), and fewer than 10% achieve Tier C (implementation-grounded, pathway-based) across all dimensions.

This classification does more than categorize studies. It demonstrates that ontological commitments made at the framing and abstraction stages determine whether resulting models can address feasibility, bottleneck diagnosis, or institutional design questions. Studies defining "the system of SDGs" as goal-indicator relationships cannot subsequently analyze implementation constraints even if advanced network metrics or analytics are later applied.

Contribution to network science methodology: This thesis advances network science methodology by providing a replicable framework for evaluating how well network abstractions preserve distinctions that are critical in the domain being studied. The eight-step structure, combined with the Tier A/B/C classification, can be adapted to other settings where implementation mechanisms matter, including infrastructure systems, policy networks, and organisational transformation processes, that is, contexts where the gap between formal structures and operational realities creates analytical blind spots. The framework also contributes a shared vocabulary and structure through which scholars can make their modelling choices explicit, justify them transparently, and defend them analytically, rather than treating such choices as neutral or purely technical decisions.

5.1.2 Architectural Contribution

Standard network analysis asks: "Is node B reachable from node A?" Implementation analysis requires: "Is B reachable from A given current verification states and institutional constraints?" This distinction motivated the gate-conditioned multiplex architecture.

The 4PIN framework treats verification and recognition decisions not as assumed outcomes but as binary decision points that condition pathway traversal. Gates (G1-G6) function as traversal constraints rather than nodes, preserving the distinction between implementation effort (building capabilities, producing outcomes) and external adjudication (verification acceptance, certification approval, registry eligibility).

The seven-layer multiplex structure prevents conflation of fundamentally different relationship types: finance conditions (L1), implementation dependencies (L2), operational outcomes (L3), value interpretations (L3BV/L3SV), and SDG attribution (L4/L5) each occupy separate layers with distinct edge semantics. Cross-layer dependencies capture how elements interact without collapsing ontological distinctions.

Contribution to network science: Gate-conditioned traversal extends standard reachability analysis to contexts where external adjudication determines pathway feasibility. This architectural pattern is transferable to other domains involving compliance verification, quality assurance, certification systems, or regulatory approval processes and therefore provides a generalizable advancement in applied network architecture, not only an SDG-specific tool.

5.2 Contribution to Sustainable Finance

5.2.1 Finance as a System of Constraints

Sustainable finance literature increasingly recognizes that capital mobilization operates through conditionality mechanisms such as covenants, performance thresholds, verification requirements, that structure implementation priorities and constrain feasible outcomes (Flammer, 2021 ; Auzepy et al., 2023). Yet, analytical tools for anticipating how specific covenant and verification designs affect implementation feasibility remain limited.

The 4PIN framework operationalizes finance as a constraint system rather than neutral capital provision. Covenants appear as nodes in Layer 1, creating binding dependencies to organizational capabilities (L2) that must be built to satisfy requirements. Environmental and Social Action Plans (ESAPs) operationalize covenant requirements through time-bound, evidence-linked implementation programs. Verification gates condition whether operational outcomes (L3) can advance to SDG attribution (L4) or value recognition (L3BV/L3SV).

The empirical application (Section 4.6) demonstrated this operationalization through documented blended finance in the Brazilian biofuel sector. Gate-state analysis revealed that outcome verification (G2) functions as a necessary gate, its failure blocks SDG attribution regardless of implementation effort. Market certification and registry eligibility gates (G4, G5) condition revenue pathways but not outcome-to-target attribution, demonstrating that business value and societal value operate through distinct mechanisms. This distinction clarifies frequent confusion between commercial sustainability narratives and rigorous SDG attribution claims.

Contribution to sustainable finance: The framework enables ex ante stress-testing of covenant and verification designs before implementation. Covenant designers can model pathway implications of alternative KPI selections, verification standards, or evidence requirements without implementing costly pilots or waiting for outcome data. This supports more robust instrument design and realistic feasibility assessment. It also supports more credible and defensible claims about contribution to sustainable development.

5.2.2 Addressing Greenwashing Structurally

Greenwashing concerns arise when sustainability claims lack verification or when outcomes are conflated with plans, intentions, or market recognition (Flammer & Bansal, 2017). The 4PIN framework addresses this through structural constraints rather than trust or disclosure alone.

The critical attribution rule, i.e. only verified operational outcomes (L3) may link to SDG targets (L4), prevents premature attribution. Business value and societal value interpretations (L3BV, L3SV) are separated from operational outcomes and SDG attribution, acknowledging that markets may recognize outcomes differently than sustainability frameworks do.

Gate failure states make implementation blockages explicit: if verification evidence is inadequate (G2 fails), downstream attribution is blocked in the model regardless of implementation claims. This transparency supports accountability by making it clear where claims rest on verified evidence versus self-assessment.

Contribution: Structural representation of verification requirements and attribution rules provides analytical discipline that disclosure frameworks alone cannot guarantee. The approach complements regulatory interventions by enabling analysis of whether institutional arrangements actually enforce claimed verification standards and by clarifying the limits of claims when they do not.

5.3 Contribution to SDG Governance

5.3.1 From Interaction Patterns to Implementation Pathways

SDG governance research has productively analyzed goal interactions, identifying synergies and trade-offs that inform policy coherence (Nilsson et al., 2016; Pradhan et al., 2017). However, knowing that goals interact does not reveal whether interactions are achievable under real constraints or where implementation stalls.

This thesis shifts analytical focus from interaction patterns to implementation pathways. The diagnostic review (Chapter 3) documented that 96% of SDG network studies model interactions among goals, targets, or indicators without representing implementation actors, processes, or mechanisms. This creates an implementation gap: models can describe relationships but cannot diagnose where feasibility fails.

The 4PIN framework fills this gap by representing the institutional infrastructure through which SDG outcomes are produced: finance arrangements that condition capital access, organizational capabilities that must be built, verification processes that validate outcomes, and recognition decisions that determine whether outcomes qualify for attribution, legitimacy, or value claims.

Contribution to SDG governance: The framework enables pathway analysis that standard approaches cannot support identifying where implementation stalls, which institutional arrangements create bottlenecks, and how design alternatives affect feasibility. This supports implementation-oriented governance rather than merely monitoring goal-level progress. It also enables governance conversations to move from abstract ambition to structured assessment of what is actually achievable.

5.3.2 Bridging National Implementation and Finance-Enabled Pathways

SDG implementation operates through multiple institutional channels: national policy frameworks, subnational service delivery, international development assistance, and increasingly, conditional finance from private and blended sources. Governance literature has examined national Voluntary National Reviews and institutional coordination mechanisms (Biermann et al., 2017), but finance-enabled pathways have received less analytical attention despite their growing scale.

The framework demonstrates that finance-enabled pathways exhibit distinct structural properties. They involve transnational actors (development finance institutions, commercial lenders, certification bodies), contractual enforcement mechanisms (covenants, ESAPs), and external adjudication (third-party verification, assurance processes) that differ from policy-driven implementation. However, both policy-led and finance-enabled channels ultimately contribute to the same SDG targets. This makes it essential to use analytical approaches capable of representing different implementation logics within a single evaluative view, rather than assuming a single, uniform pathway to SDG outcomes.

Contribution: The framework provides a template for analyzing finance-enabled SDG pathways that can complement national implementation analysis. By making conditionality, verification, and attribution explicit, it enables systematic comparison of how different implementation channels, including policy-driven, finance-enabled, community-based, produce and validate SDG contributions. This creates a more integrated understanding of SDG delivery ecosystems.

5.4 Limitations, Extensions and Future Research

5.4.1 Limitations of the Current Framework

Single-Case Demonstration

The empirical application relies on a single well-documented case (Brazilian biofuel sector). This demonstrates analytical feasibility and decision relevance but limits claims about generalizability across sectors, geographies, or finance instrument types. The framework is transferable in principle, but each application requires case-specific instantiation and evidence.

Documentary Dependence

The framework requires documented finance terms, implementation plans, verification reports, and certification records. Where documentation is sparse, confidential, or non-standardized, instantiation becomes difficult. This creates a selection bias toward well-documented transactions.

Static Representation

The current implementation treats gates as binary states (PASS/FAIL) at a given time, but does not model temporal dynamics. Dynamic extensions would require longitudinal evidence and temporal network analysis.

Boundary Constraints

The framework focuses on firm-proximate, documentable pathways. It does not capture broader system effects, spillovers, or indirect impacts. This supports attribution precision but limits system-level analysis.

Actor Representation

Actors appear implicitly rather than explicitly modeled. This protects analytical discipline but limits the ability to analyse strategic behaviour, power asymmetries, or negotiation processes.

5.4.2 Extensions and Future Research Directions

The framework developed in this thesis establishes analytical foundations for implementation-grounded SDG network analysis. At the same time, it opens a set of concrete research pathways that can extend, deepen, and test the framework across domains, contexts, and analytical traditions.

Cross-Case Comparative Analysis

A first direction concerns systematic cross-case analysis. Future research should apply both the diagnostic framework (Chapter 3) and the 4PIN architecture (Chapter 4) to broader empirical corpora and additional documented finance-enabled cases.

Comparative work could examine variation along three dimensions:

- **Instrument type:** green bonds, sustainability-linked loans, blended finance, impact investing structures, project finance
- **Sector:** agriculture, renewable energy, extractives, infrastructure, manufacturing
- **Geographic and regulatory context:** developed and developing economies, different disclosure regimes, varying institutional capacities

Comparative studies would make it possible to test whether architectural properties of pathways such as gate concentration, redundancy, bottleneck types, and dependence on verification rigor, vary systematically or whether recurring structural patterns emerge. Such work would support movement from single-case analytical insight toward cumulative knowledge and potential typologies of finance-enabled SDG pathways.

Temporal Extensions

A second research direction concerns time. The current framework establishes feasibility and constraint structure at a given analytical moment. Many implementation realities, however, unfold as processes.

Future research could develop dynamic 4PIN variants capable of representing:

- the evolution of capabilities over time
- changing verification standards and evidence thresholds
- remediation cycles following gate failure
- pathway resilience under changing conditions

This would require both methodological development and longitudinal evidence, but would enable analysis of implementation stability, vulnerability, institutional learning, and adaptation, all of which are central questions in sustainability governance.

Integration with Impact Evaluation

The current framework focuses on feasibility, bottlenecks, and constraint architecture. It does not estimate causal impact and does not claim to.

A productive research frontier lies in integration between implementation-grounded structural analysis and causal evaluation approaches. Possible directions include:

- using 4PIN pathway structure to identify plausible mechanisms prior to causal inquiry
- employing gate structures as quasi-institutional instruments for empirical identification
- combining pathway feasibility analysis with econometric outcome estimation

Such integration would strengthen the connection between implementation structure, realized outcomes, and causal claims, improving both analytical rigor and policy relevance.

Actor-Oriented Extensions

While the framework deliberately centers documented institutional structures, future work may extend it by explicitly incorporating actors.

Potential developments include:

- representing lenders, borrowers, verifiers, certifiers, regulators, and community actors as nodes
- incorporating power asymmetries, negotiation processes, and strategic behavior
- linking institutional constraints to governance dynamics

This would allow the analysis not only of documented institutional architectures, but also of the political economy and governance relationships that shape whether these architectures function effectively.

Hypergraph and Higher-Order Interaction Extensions

Many sustainability processes depend on coordinated actions by multiple actors rather than pairwise interactions. Hypergraph methods offer a natural extension.

Future research could explore:

- multi-party verification and co-certification requirements
- covenants requiring compliance by borrowers and suppliers simultaneously
- community consent processes involving multiple decision bodies

Such approaches would deepen analysis of coordination dependence, collective failure modes, and resilience of multi-actor implementation systems, addressing a methodological blind spot identified in Chapter 3.

Tool Development and Practitioner Accessibility

Finally, a practical frontier concerns translation into tools that are usable in institutional settings.

Future research could contribute by developing:

- semi-automated document parsing for network instantiation
- user interfaces for gate-state modeling and pathway exploration
- standardized visualization and reporting formats
- open-source software enabling broader adoption

Such developments would lower the technical and resource thresholds required to use the framework, enabling uptake by development banks, DFIs, sustainability-linked lenders, assurance firms, and SDG monitoring institutions. This would support not only academic innovation but also real-world decision capability.

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Annex 1

Supplementary material “*Evaluating SDG Network Models: A Network Science Ontology-Based Framework: Literature Scoping Review*” is available at <https://zenodo.org/records/17850647>

The aim for this literature scoping review is to investigate how academic journal papers have described how network science and its analysis methods are applied to the interrelations between the UN 2030 Agenda Sustainable Development Goals (SDG) and associated targets and indicators.

Annex 2

Supplementary Tables for the 4PIN SDG Network Framework Review are available at <https://zenodo.org/records/17238185>

This dataset contains the structured tables underlying the manuscript's figures and statistics. Sheets include:

1. Study list with bibliographic metadata,
2. Coding matrix across the eight methodological steps and four phases,
3. Tier assignments and decision notes,
4. Summary statistics and pivot tables used in the Results,
5. Crosswalks for figure generation.

Annex 3

Supplementary data for 4PIN: a four-phase framework for the implementation and analysis of Sustainable Value Creation Plan networks is available at <https://zenodo.org/records/18089974>

This dataset provides the materials used in the empirical application of the Four-Phase Implementation Network (4PIN) framework. It includes (i) a Gephi file encoding the seven-layer 4PIN multiplex network, representing finance conditionality, implementation capabilities, operational outcomes, business and societal value interpretations, SDG targets, and SDG goals; and (ii) an Excel evidence register linking every node and relation to documented sources.

The network file preserves ontological distinctions and supports feasibility-oriented pathway analysis, while the evidence register provides full traceability to finance agreements, verification reports, certification records, and sustainability disclosures. Together, these files enable transparency, reproducibility, and methodological development in SDG implementation and sustainable finance research.

Annex 4

The *4PIN Finance-Enabled SDG Implementation Ontology* is available at <https://rjlop.github.io/fourpin/docs/index.html>,

The 4PIN Finance-Enabled SDG Implementation Ontology provides a formal vocabulary for representing how conditional finance, capability investments, verification decisions, and SDG attribution are linked in sustainable finance transactions. It defines core classes such as Blended Finance Vehicle, Capability Investment Commitment, Capital Flow, Covenant, ESAP (Environmental and Social Action Plan), Eligibility Rule, Pricing Adjustment Rule, and Recognition Decision, together with object properties that capture how capital flows, conditions, action plans, capabilities, outcomes, evidence, and SDG targets relate to one another.

The documentation site offers human-readable descriptions of all classes and properties, downloadable serialisations of the ontology (JSON-LD, RDF/XML, N-Triples, Turtle), and links to visualisation tools such as WebVOWL. It is intended as a reusable, implementation-grounded schema for researchers and practitioners working on SDG implementation, sustainable finance, and network-based analysis of conditionality and verification structures, and it aligns directly with the 4PIN framework used for multiplex network modelling in the associated research.