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Agent-Based Model for the Assessment of Biomass Supply Chain for Biogas and Biomethane

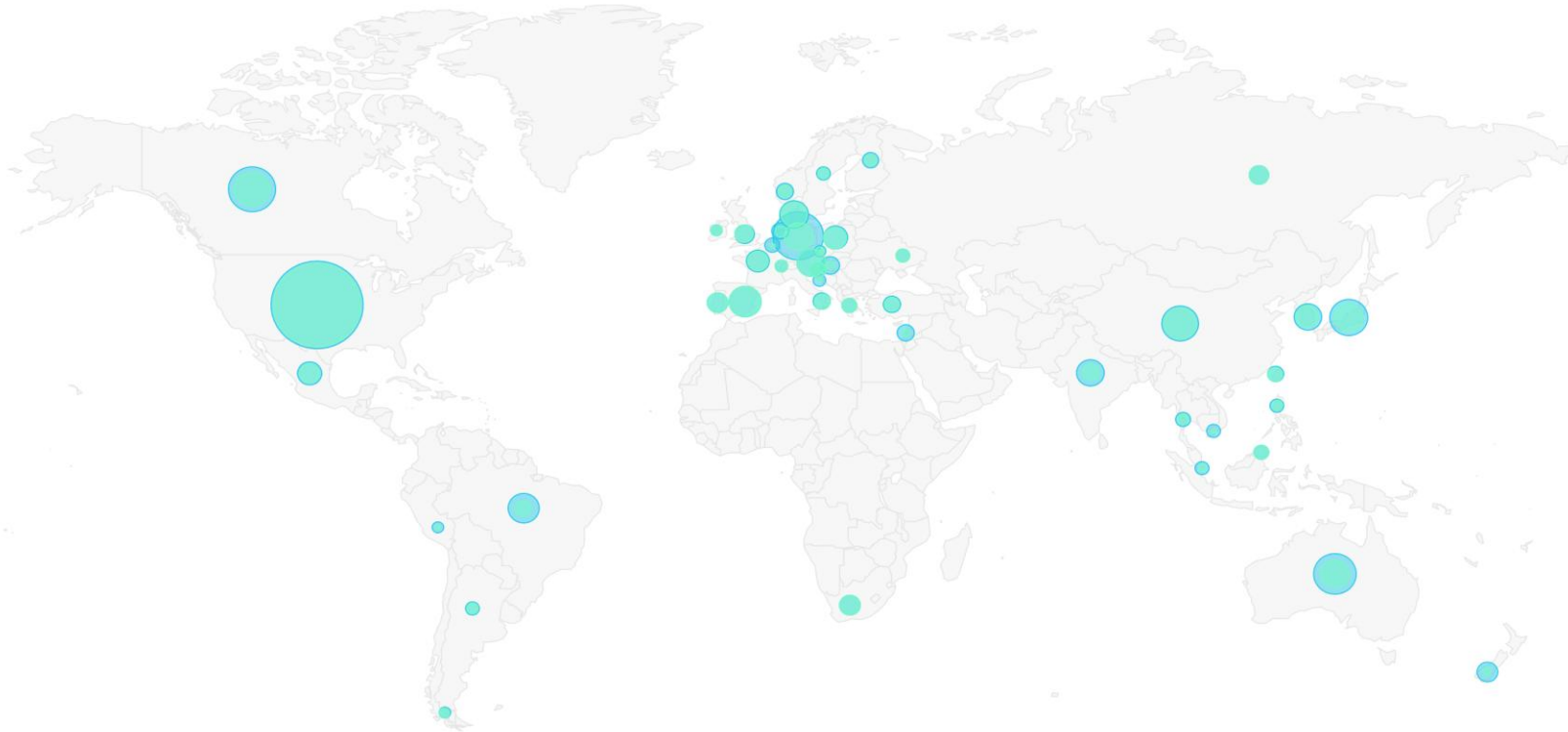
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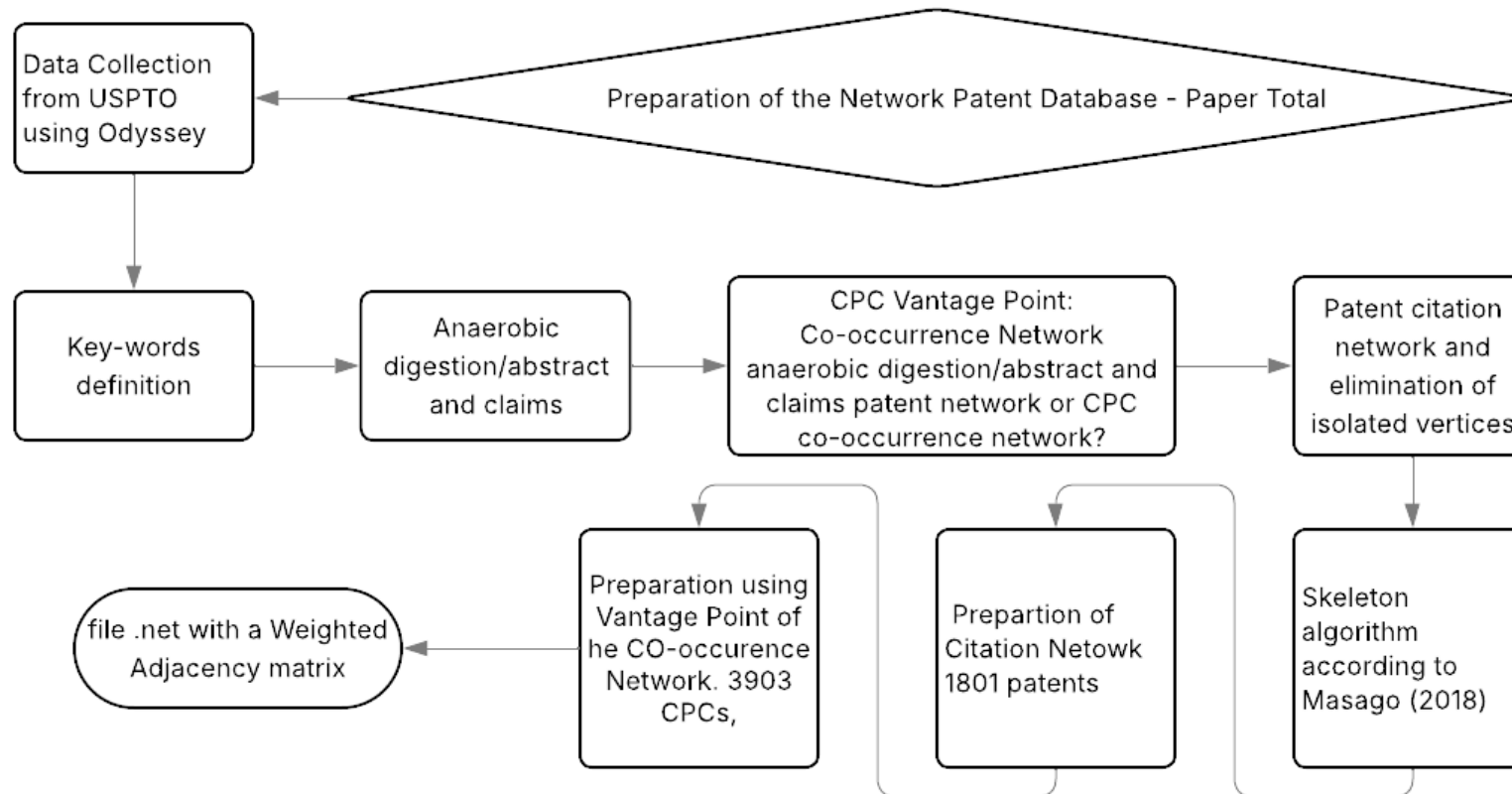
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Worldwide Activity

PN=(AU199190914 A1 OR AU704279 B2 OR BE1004311 AD OR BR8304406 A OR BRP19405922 A OR CA2451597 AA OR CA2451597 C OR CA2468158 AA OR CA2468158 C OR....



• basic methodology

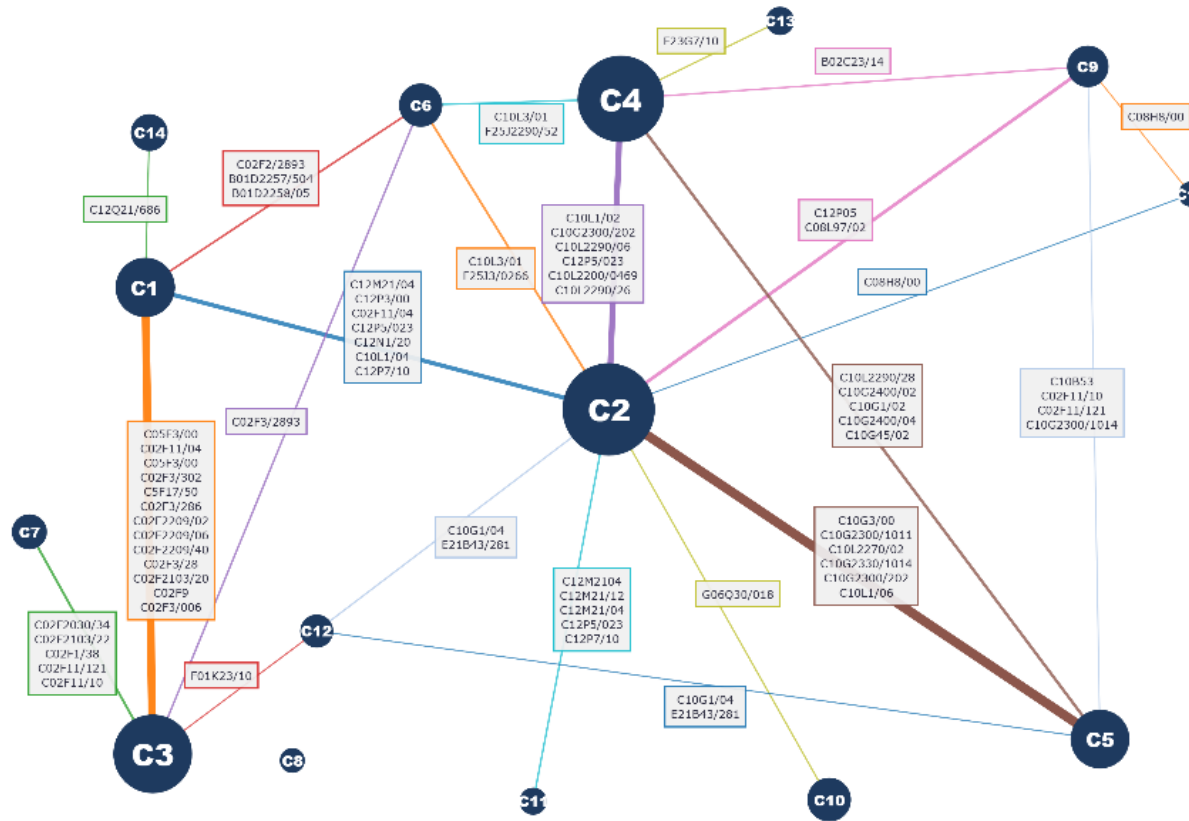


Network characteristics of a reduced 1485 CPC co-occurrence network

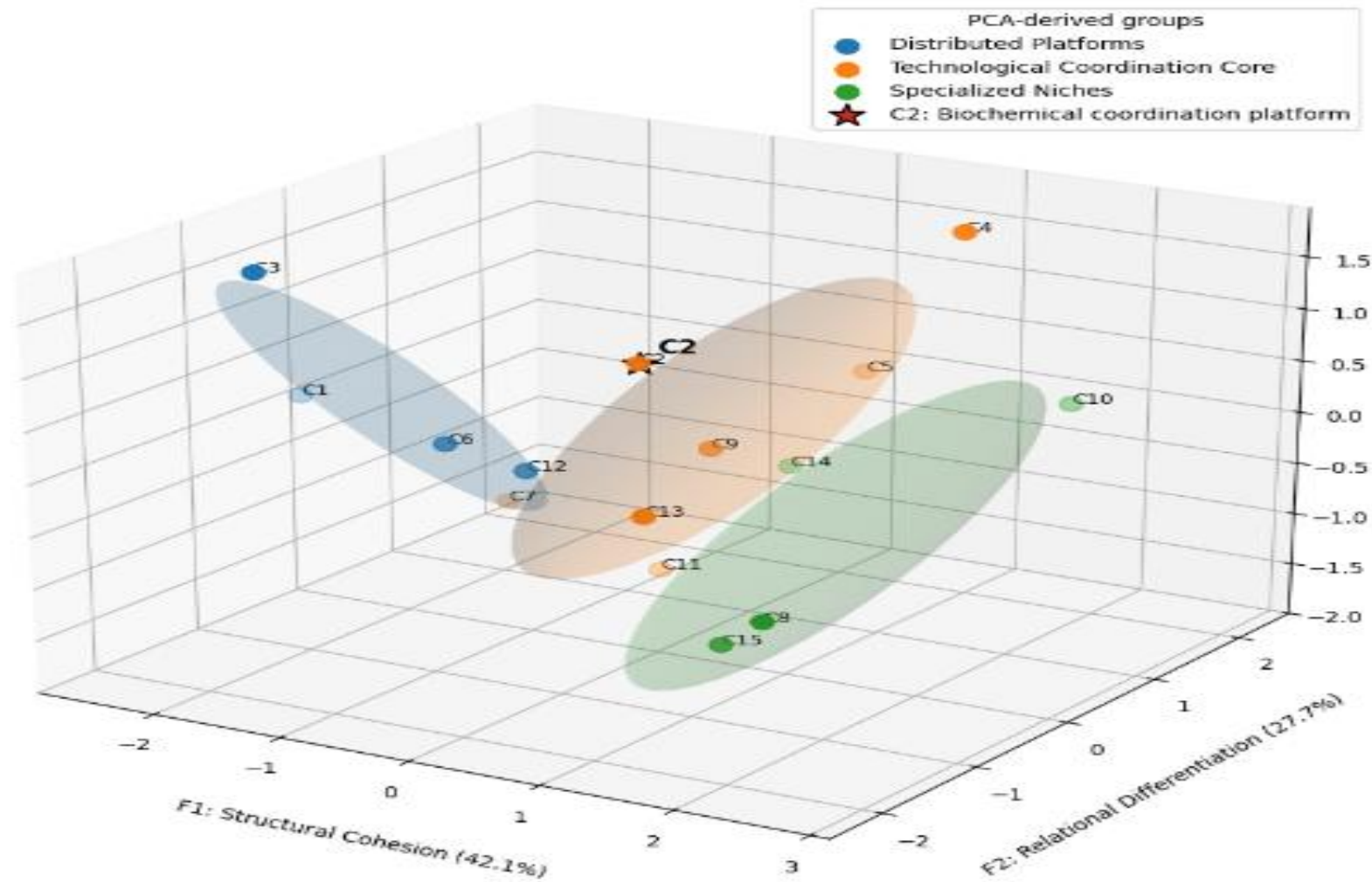
Cluster	NCPC	AVDEG	Density	ANLI	Assort.	TransR	Specialization
1	245	33.6	0.07	162.1	-0.09	0.28	0.62
2	121	67.0	0.28	677.4	-0.02	0.84	0.64
3	350	45.5	0.06	213.4	-0.01	0.32	0.81
4	67	64.6	0.48	1296.3	0.10	2.12	0.80
5	59	51.5	0.44	685.0	0.48	5.00	0.69
6	148	33.5	0.11	178.1	-0.09	0.92	0.78
7	101	29.0	0.14	105.1	0.24	1.42	0.51
8	8	10.0	0.71	78.0	-0.30	1.33	0.94
9	90	67.1	0.38	252.0	0.36	3.14	0.78
10	38	74.0	0.97	777.0	n.d.	10.00	0.95
11	28	21.1	0.38	91.2	0.25	2.48	0.53
12	106	28.9	0.14	118.1	0.02	1.00	0.87
13	50	27.8	0.27	110.6	0.13	1.26	0.84
14	61	65.4	0.53	313.0	0.09	1.80	0.97
15	13	17.5	0.73	54.0	-0.35	7.85	0.82
Mean	99.00	42.43	0.38	340.75	0.06	2.65	0.77
CV	0.93	0.50	0.71	1.05	3.87	0.96	0.18

Source: Network data and indexes elaborated by the authors using Pajek and Python.

Sintetic network (global cluster view) and links

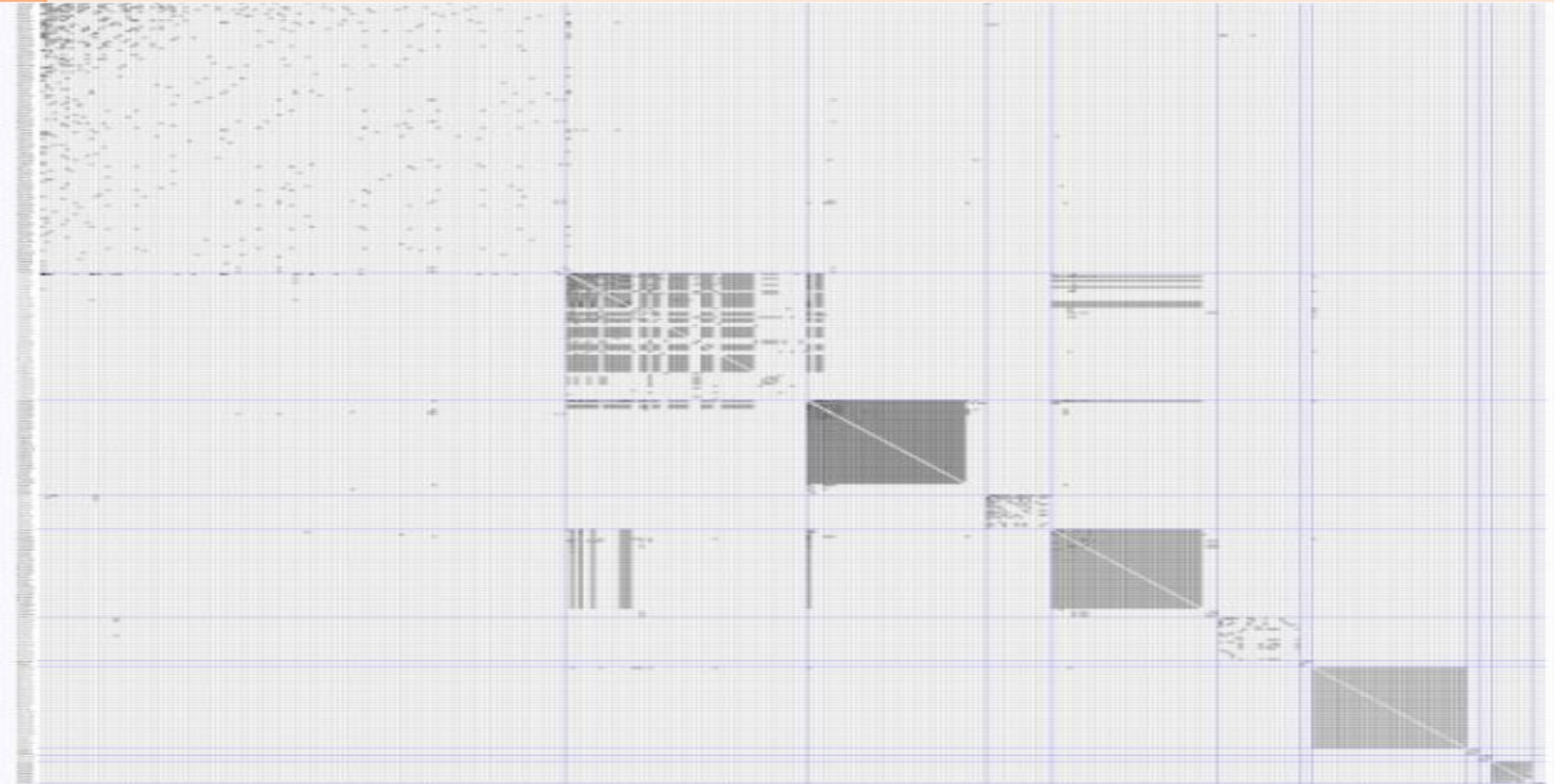


3D PCA Factor Space of Biogas Technology Clusters
without AVDEG and TransR

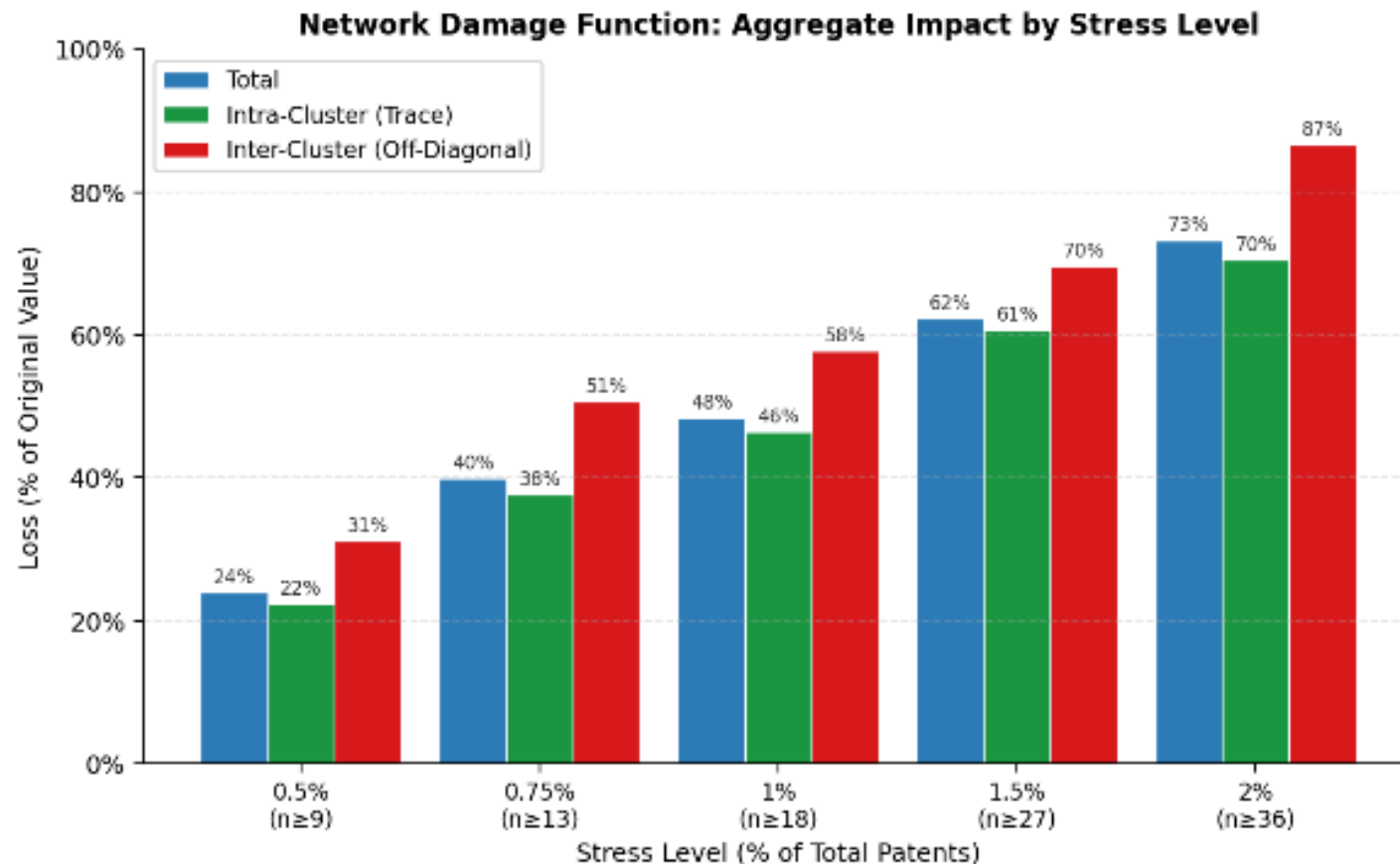


F3: Scale-Interaction Capacity (17.3%)

The eight main clusters: are they interpretable?



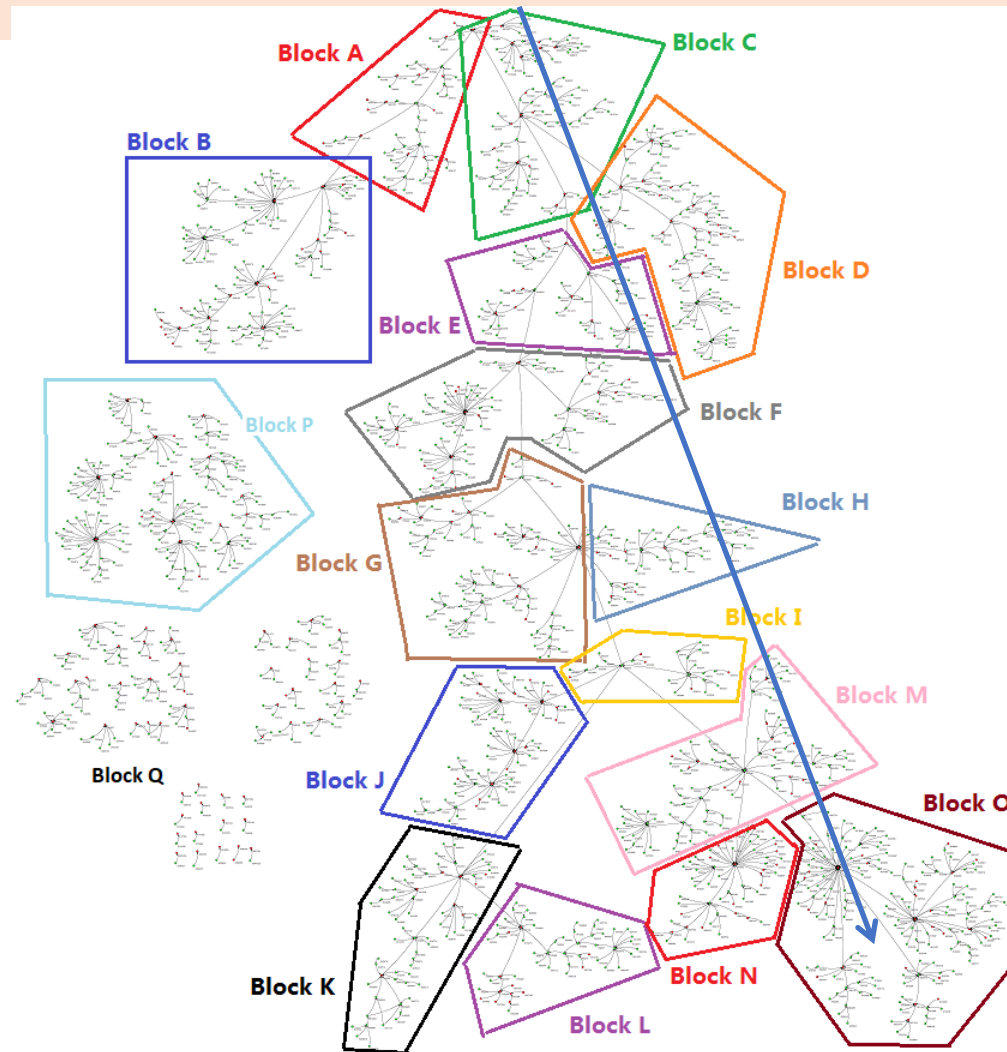
Stress text results: resilience



Methodology – Biogas: Topological Skeleton End Points.

Trying to go further

- Biological treatment of effluents and digesters; (*connection with water treatment and algae systems*);(*connect*)
- Solids separation fertilizers; (*derivation to biofertilizers and circular economy*);
- Biogas from the treatment of effluents and agricultural residues; (*connect*)
- MSW and Solid Waste;
- Hydrogen for fuel production; (*derivation to Hydrogen economy*)
- Fuel cell for generating electricity and heat; (*derivation to alternative fuels*)
- Thermal decomposition reactor for converting organic waste into biogas;
- Microalgae for bio-oil roduction; (*connection with other TT*)
- Integrated ethanol and biogas production process; (*derivations towards na integrated system*)
- Internal combustion engine lubricants;
- pyrolysis system;
- Hybrid fuel of biofuel and diesel gas;
- biogas ignition engine



Central proposition

An ABM of biogas should not model “the representative biogas firm”; it must model differentiated technological functions and their interdependencies.

THESIS

Functional heterogeneity is the bridge between the CPC co-occurrence network and an operational ABM.

1. Agents differ by function

Actors specialize in core AD, water treatment, microbiology, feedstock logistics, gas/energy conversion, monitoring, certification, or extensions.

2. Interactions are modular

The technology system evolves through complementarities, bridges, bottlenecks, and recombination across functional layers.

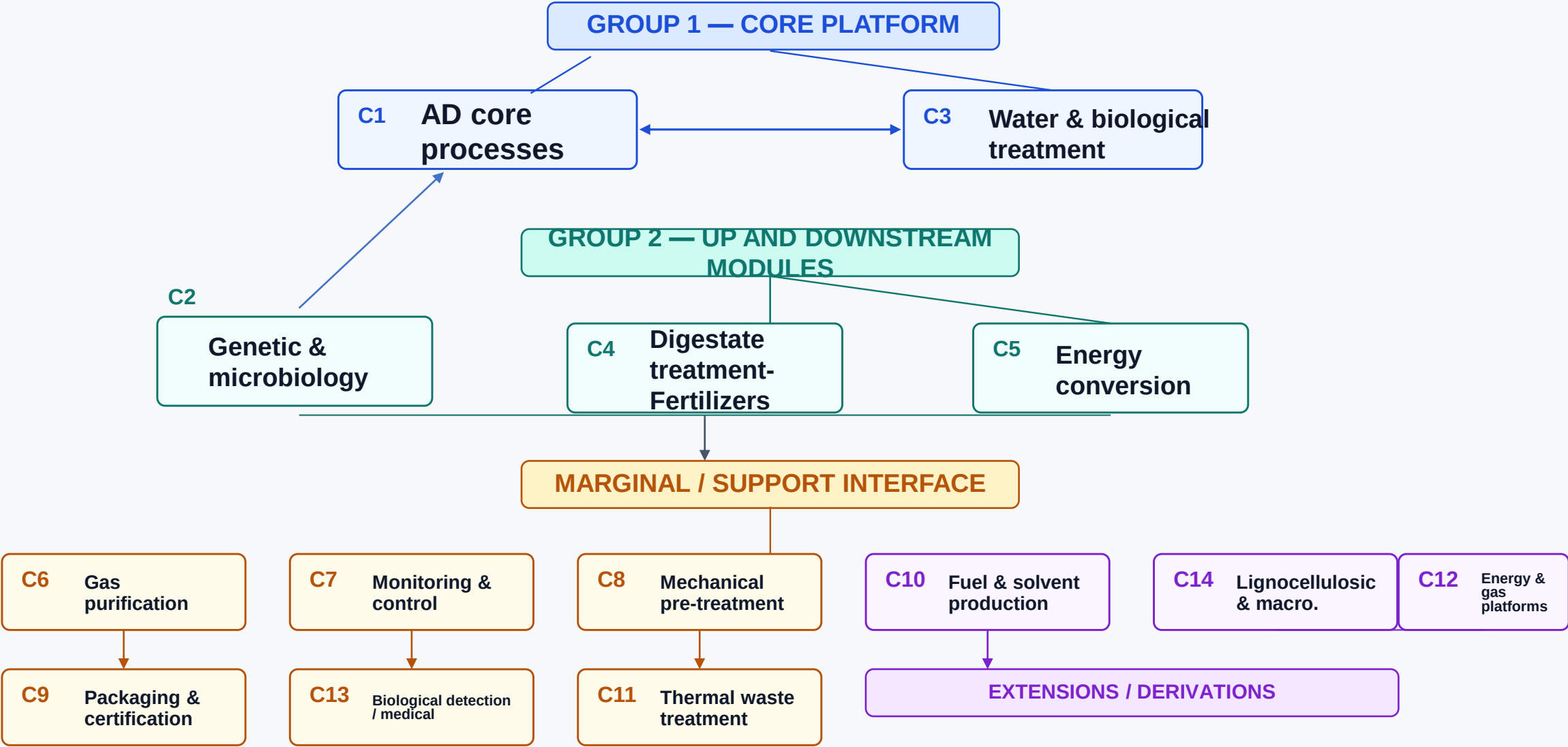
3. Outcomes are emergent

Diffusion, upgrading, diversification, lock-in, resilience, and environmental performance result from local decisions and network structure.

ABM implication: each cluster family becomes a distinct modelling demand, not just a label in a descriptive taxonomy.

Functional architecture of the biogas technology system

Editable reconstruction of the supplied diagram: from core platform to downstream modules, support interfaces, and extensions.



Four layers of heterogeneity, four modelling demands

The same technology system combines a platform core, modular downstream functions, support interfaces, and derivative trajectories.

Core platform

C1 + C3

ABM demand: model system viability and plant-level stability.

Typical agents: AD operators, wastewater managers, engineering firms.

Main variables: installed AD capacity, substrate mix, process stability, treatment standards, water/sludge constraints.

Up and Downstream modules

C2 + C4 + C5

ABM demand: model technological upgrading and module adoption.

Typical agents: biotech firms, digestate processors, utilities, energy converters.

Main variables: conversion efficiency, digestate quality, biogas upgrading, capital cost, learning-by-doing.

Support interface

C6 + C7 + C8 + C9 + C11 + C13

ABM demand: model bottlenecks, coordination costs, and regulatory interfaces.

Typical agents: logistics suppliers, sensor firms, certification bodies, equipment providers.

Main variables: feedstock reliability, monitoring quality, certification status, waste-treatment options.

Extensions

C10 + C12 + C14

ABM demand: model diversification and path creation.

Typical agents: fuel producers, gas platform firms, lignocellulosic technology developers.

Main variables: R&D portfolio, market entry, complementary assets, risk, policy pull.

Design principle: the ABM must preserve functional roles while allowing cross-cluster recombination.

ABM Core: Methane as the Main Output

A model centered on the production and valorization of methane and biomethane

Feedstock

Technology

Decisions

Outcomes

State variables

- Feedstock availability and quality
- Plant scale and installed capacity
- Conversion efficiency and gas upgrading
- Capital, operating costs, and prices

Agent decisions

- Adopt or delay anaerobic digestion
- Choose upgrading and purification strategies
- Coordinate with suppliers and buyers
- Allocate output between energy, gas, and by-products

Expected outputs

- Methane and biomethane production
- Cost competitiveness
- Technology diffusion across sectors
- Environmental co-benefits and circularity

Model logic

The ABM should capture how heterogeneous capabilities and incentives affect the expansion of methane-oriented biogas systems over time.

Agent taxonomy: from clusters to model actors

ABM agents should represent functional positions in the technology system, not only sectors or firm size. Should we pick up representative firms?

AGENTS

AD plant operators

Run C1/C3 assets; decide on process upgrades and substrate allocation.ex. Sugarcane Mills

Feedstock suppliers

Provide biomass flows; they differ in seasonality, quality, distance, and contract reliability. Vinasse, MSW

Biotech / R&D actors

Search genetic, microbial, and enzymatic improvements; transfer knowledge to plants.

Regulators / certifiers

Set treatment standards, gas-quality rules, digestate-use constraints, and certification requirements.

Wastewater & waste managers

Supply environmental treatment demand; connect sludge, effluent, and digestate routes.

Technology suppliers

Offer modules: pre-treatment, sensors, bioreactors, gas cleaning, conversion, thermal treatment.

Energy and fuel market agents

Value electricity, heat, biomethane, solvents, and derivative products.

Users/adopters

Create demand for outputs: renewable fuels, energy, fertilizers, biocarbon, carbon credits, and certified recycled products.

The same empirical firm can be a multi-function agent if its patent portfolio or operations *span* several clusters.

State variables: what each agent must carry

Functional heterogeneity requires richer internal agent states than a simple adoption / non-adoption variable.

Technological portfolio

Which modules are installed or mastered: AD core, treatment, microbiology, gas upgrading, monitoring, logistics, extensions.

Capabilities and absorptive capacity

R&D capability, engineering competence, operational know-how, and ability to recombine knowledge across clusters.

Resource position

Feedstock access, plant scale, capital constraints, energy market access, logistics distance, infrastructure quality.

Performance profile

Yield, process stability, methane purity, digestate compliance, emissions, water-treatment performance, costs.

Network position

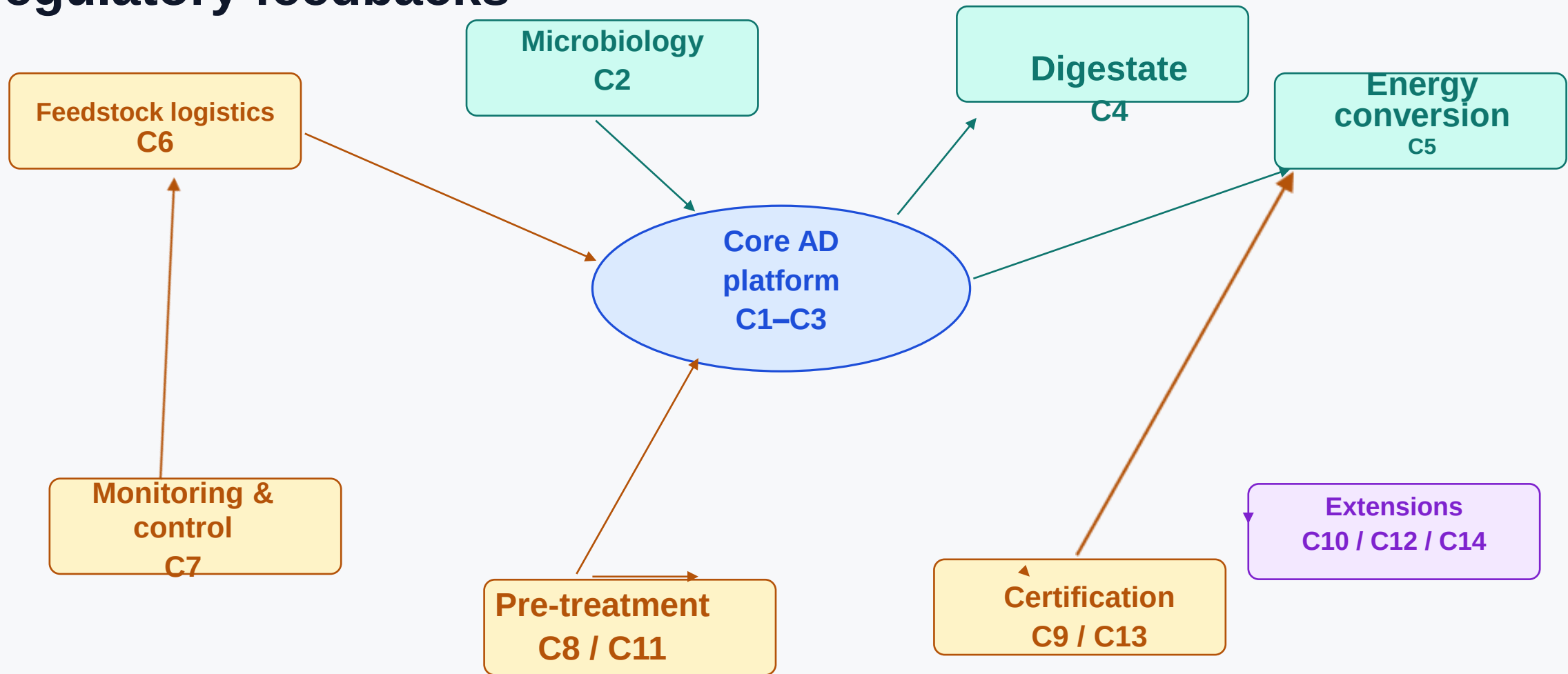
Partners, bridges to other functions, knowledge proximity, prior collaboration, supplier/customer ties.

Regulatory exposure

Certification status, environmental restrictions, gas grid standards, waste-disposal rules, incentive eligibility.

ABM demand: state variables must be cluster-sensitive, because each function imposes different constraints and opportunities.

Interaction structure: material flows, knowledge flows, and regulatory feedbacks



Three networks should co-exist in the ABM

Material flows connect feedstock, waste, digestate, and energy; knowledge flows connect learning and technological search; regulatory feedbacks connect certification, environmental standards, and market access.

The model should use a multilayer network rather than a single homogeneous interaction graph.

Behavioral rules: decisions differ by functional position

ABM rules should translate functional roles into operational choices.

Adoption rule

Agents adopt modules when expected gains exceed cost, risk, and compatibility constraints.

Search rule

Agents search locally inside their function or recombine across bridges when policy, market, or performance pressure rises.

Learning rule

Efficiency improves through learning-by-doing, supplier learning, and feedback from monitoring/control systems.

Partnership rule

Agents form ties when complementarities are high, distance is manageable, and standards are compatible.

Exit / lock-in rule

Agents persist with existing modules when sunk costs, standards, or network dependence make switching difficult.

Policy response rule

Regulations and incentives change thresholds for adoption, certification, gas quality, and waste-treatment options.

Core point: the “same” adoption decision has different determinants in microbiology, energy conversion, digestate treatment, and certification.

ABM design matrix: functional block → model requirement

A practical crosswalk for translating the diagram into model architecture.

Functional block	Agent representation	Key state variables	ABM outputs
C1–C3 Core platform	Plant operators; wastewater/treatment managers; engineering providers	Process stability; treatment compliance; installed capacity; substrate mix	Viability of AD systems; bottlenecks; resilience of core platform
C2–C4–C5 Downstream modules	Biotech firms; digestate processors; utilities; energy converters	Conversion yield; digestate quality; upgrading cost; module compatibility	Adoption paths; upgrading waves; energy/digestate value creation
C6–C7–C8–C9–C11–C13 Support interface	Logistics firms; sensor providers; certifiers; equipment and thermal-treatment firms	Feedstock reliability; monitoring accuracy; certification status; pre-treatment capacity	Coordination failures; certification delays; performance variance
C10–C12–C14 Extensions	Fuel/solvent firms; gas platform actors; lignocellulosic developers	R&D intensity; market access; policy pull; complementarity with core	Diversification; path creation; niche emergence; lock-in or transition

The model should estimate not only “how much biogas is adopted”, but which technological configuration becomes dominant.

Scenario architecture: what the ABM should be able to test

Functional heterogeneity creates several families of experiments.

Feedstock shock

Stress C6: seasonality, logistics cost, feedstock quality, and contract reliability.

Core efficiency policy

Target C1/C3: subsidies, standards, technical assistance, and wastewater integration.

Biotech breakthrough

Target C2: microbial/genetic improvements that increase yield or operational stability.

Digestate regulation

Target C4/C9: certification, nutrient standards, and market creation for biofertilizers.

Energy-market pull

Target C5/C12: biomethane, power/access, fuel incentives, carbon eat, grid value.

Network bridge removal

Test resilience: remove or weaken links between support modules, core platform, and extensions.

Monitoring upgrade

Target C7: reduce information asymmetry and process failure with sensors/control.

Diversification path

Target C10/C14: transition toward fuels, solvents, and lignocellulosic platforms.

Useful comparison: baseline descriptive network vs. counterfactual ABM trajectories under alternative policy, market, and technological shocks.

Outputs and validation: how to judge the ABM

The ABM should reproduce structural features of the technological system and generate interpretable counterfactuals.

Model outputs

- Adoption of modules by agent type
- Emergence of core–periphery structures
- Cross-cluster recombination and diversification
- Bottlenecks in feedstock, certification, or monitoring
- Environmental and energy performance
- Resilience after link or policy shocks

Calibration inputs

- CPC co-occurrence network by cluster
- Patent-holder specialization profiles
- Cluster centrality, bridging, and density measures
- Historical sequences of patenting/adoption
- Market prices, policy rules, and technical parameters
- Expert assumptions for behavioral thresholds

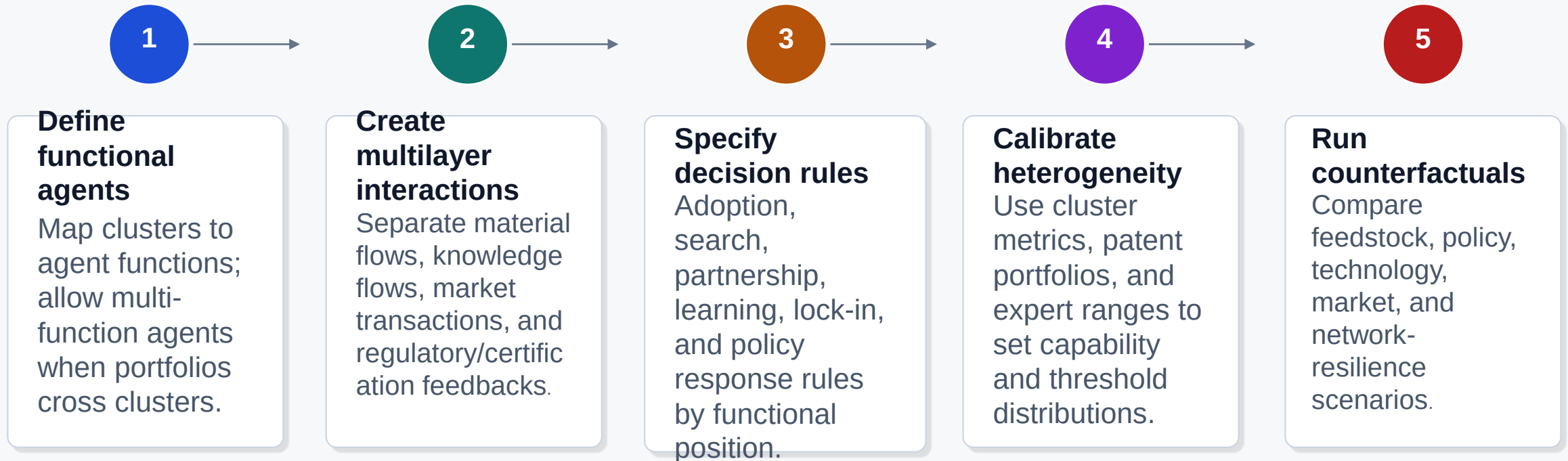
Validation logic

- Does the ABM reproduce observed modularity and core–support relations?
- Does it reproduce plausible specialization and diversification?
- Are simulated bottlenecks consistent with cluster-link evidence?
- Are policy results robust to threshold and learning assumptions?

Validation should combine network fit, qualitative plausibility, and scenario sensitivity—not a single aggregate prediction.

Implementation roadmap

A staged route from the CPC network to an operational ABM.



Minimum viable ABM: heterogeneous agents + functional modules + multilayer links + behavioral rules + policy/market scenarios.

Take-home message

The diagram provides a direct modelling grammar for an ABM of biogas technology evolution.

Functional heterogeneity should be treated as the structural foundation of the ABM. The clusters indicate where agents differ, what they exchange, which constraints bind them, and which transition pathways are plausible.

Model the core

C1–C3 define system viability and basic technological coherence.

Model the modules

C2–C5 define upgrading, value creation, and specialization.

Model the interfaces

C6–C13 define coordination, bottlenecks, certification, and resilience.

Model extensions

C10–C12–C14 define diversification and new technological trajectories.

Result: a model capable of explaining not only diffusion, but the endogenous formation of technological configurations.

Firm Specialization and Systemic Functions in Biogas Technologies

A classification of key firms as underpinning, enabling, GPT-like or complementary actors

Underpinning

Operational base: sanitation, water, sludge, equipment and AD infrastructure.

Enabling

Conversion and upgrading routes that open new technological trajectories.

GPT-like

Recombinable industrial capabilities used across several sectors.

Complementary

Circular-economy and adjacent technologies that close or broaden the system.

Core claim: the biogas system is functionally heterogeneous and modular.

Functional lens for classifying firms

The same firm may perform more than one function when it crosses clusters.

Underpinning

Provides the operational and environmental base for anaerobic digestion and waste treatment.

Siemens Water, Evoqua, Degremont, EBARA, Anaergia

Enabling

Creates or improves routes for biomass conversion, gas upgrading and CO₂ separation.

Xyleco, Virent/WARF, Ensyn, Alstom, CO2 Solution

GPT-like

Broad capabilities that can be recombined across sectors and technological applications.

logen, Siemens, EBARA, Alstom, Lummus Technology

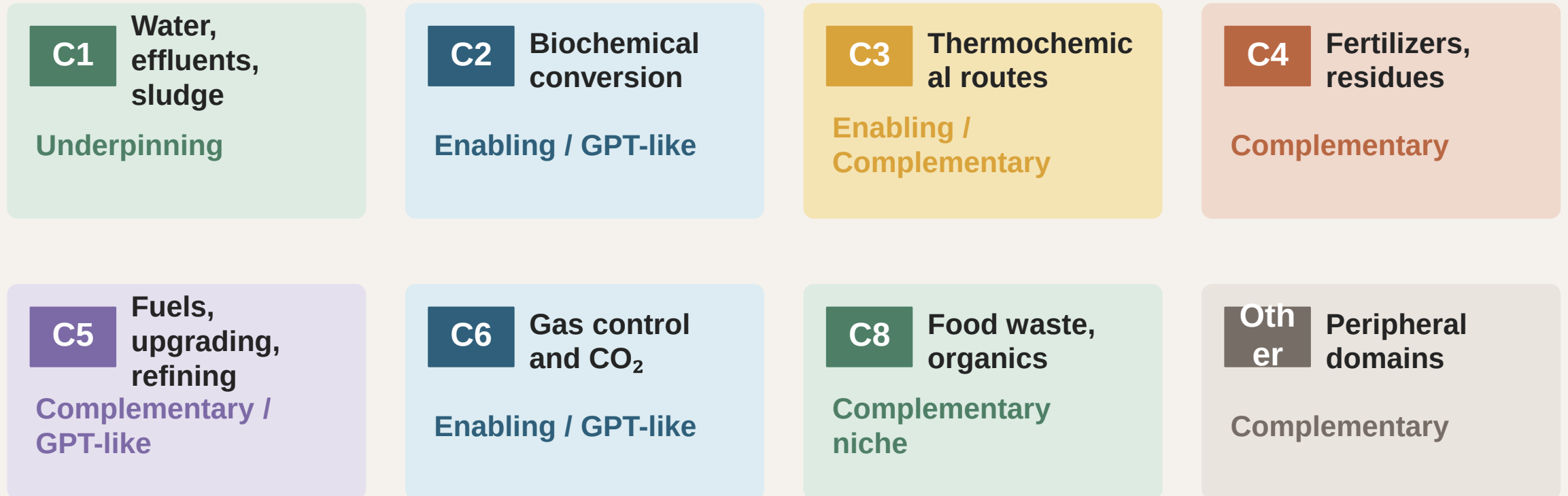
Complementary

Closes loops or connects the system to fertilizers, food waste and peripheral domains.

Anuvia, EarthRenew, Divert, QED, GlassPoint Solar

Cluster × function map

Clusters differ by content and by systemic role.



Reading: C1 anchors the system; C2, C3 and C6 enable upgrading; C4, C8 and peripheral clusters close or broaden the system; C5 links biogas to established fuel chains.

Underpinning and residue valorization

C1 provides the operational base; C4 closes agricultural material cycles.

C1 Water, effluents, sludge, digestion

Most important firms

Heartland Technology Partners
Siemens Industry / Siemens Water
Evoqua
Degremont
Anaergia

UNDERPINNING

Environmental infrastructure, wastewater treatment, sludge handling and AD operation.

C4 Fertilizers and organic residues

Most important firms

Vitag Holdings
Magic Dirt
Anuvia Plant Nutrients
EarthRenew / EarthRenew Organics

COMPLEMENTARY

Transforms organic residues into fertilizers, nutrients and agricultural inputs.

Alternative biomass conversion routes

C2 and C3 expand the system beyond strict anaerobic digestion.

C2

Biomass and biochemical conversion

Most important firms

Xyleco
Shell Oil
Pennsylvania Sustainable Technologies
Virent / WARF

ENABLING / GPT-LIKE

Biochemical conversion, lignocellulosic processing, green chemistry and advanced biofuels.

C3

Thermochemical conversion and bio-oil

Most important firms

Ensyn Renewables
Biomass Energy Enhancements
Pharmatherm Chemicals

ENABLING / COMPLEMENTARY

Pyrolysis, gasification, bio-oil, biochar and renewable fuel routes.

Industrial upgrading, fuels and gas control

C5 and C6 introduce heavier industrial capabilities.

C5 Fuels, upgrading and refining

Most important firms

Lummus Technology
Fording Coal
PanCanadian Petroleum

COMP. / GPT-LIKE

Refining, hydrocarbon processing and process engineering linked to broader fuel chains.

C6 Gas control and CO₂

Most important firms

Alstom Technology
ADA-ES
Carolla Engineering
CO2 Solution

ENABLING / GPT-LIKE

Gas cleaning, emissions control, CO₂ removal and biomethane/RNG upgrading.

Complementary niches and peripheral domains

C8 and “Other” clusters organize residues or connect adjacent technologies.

C8 Food waste and organics

Most important firms

Divert Inc.

COMP. NICHE

Highly concentrated niche linking food waste logistics, residue recovery and AD.

Other Peripheral domains

Most important firms

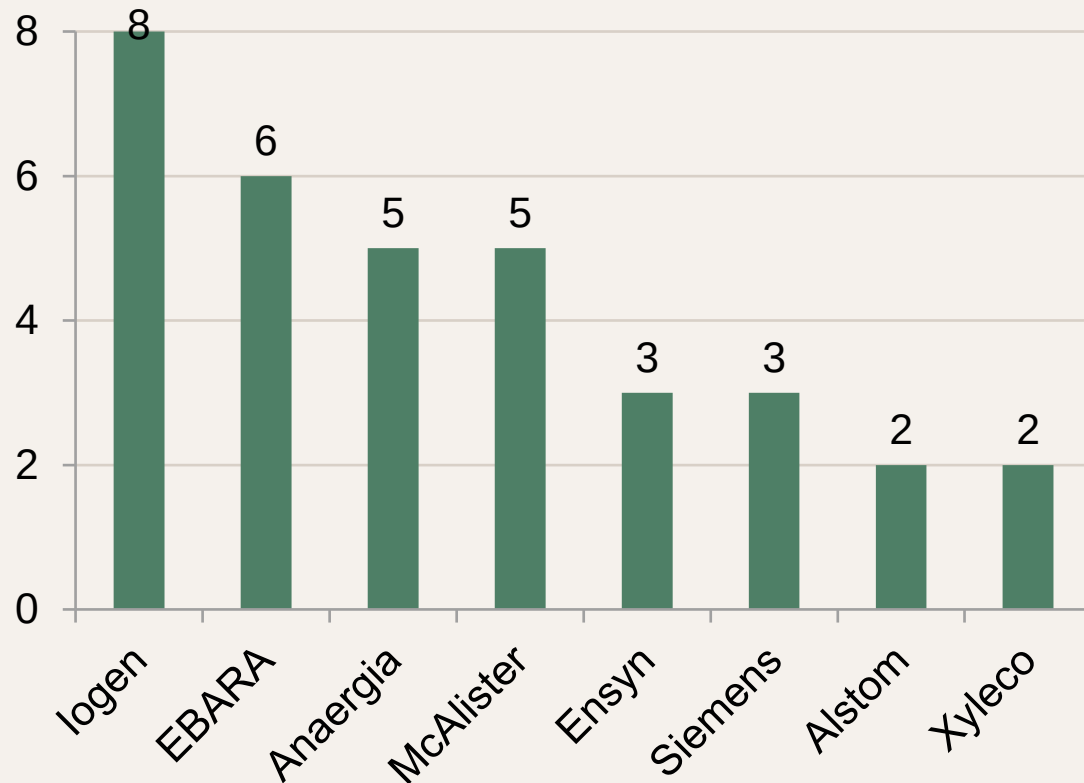
GlassPoint Solar
Watershed Geosynthetics
QED Environmental Systems

COMPLEMENTARY

Solar thermal, landfill, geosynthetics and adjacent environmental solutions.

Transversal actors: recombination capability

Recurrence across several clusters indicates bridges across biomass, waste, gas and fuels.



Iogen

Most transversal actor: biofuels, biomass, RNG and waste conversion.

Anaergia

Integrates AD, organic waste, biogas/RNG and fertilizers.

EBARA / Siemens / Alstom

Engineering suppliers connecting equipment, sanitation, gas and energy.

Ensyn / Xyleco / McAlister

Bridges biomass routes, conversion technologies and fuels.

Most strategic firms by systemic function

The most relevant actors are those combining specialization and cross-cluster reach.

Firm or group	Function	Why it matters
logen	Enabling / GPT-like	Biofuels, biomass, RNG and waste conversion.
Anaergia	Underpinning + complementary	AD integration, organic waste, biogas/RNG and fertilizers.
EBARA / Siemens	Underpinning / GPT-like	Equipment, sanitation, treatment systems and energy links.
Alstom / CO2 Solution	Enabling / GPT-like	Gas control, CO ₂ removal, emissions and upgrading.
Xyleco / Virent / WARF	Enabling	Biochemical conversion and lignocellulosic biomass routes.
Ensyn	Enabling	Thermochemical conversion, bio-oil and renewable fuels.

Synthesis: a heterogeneous and modular system

Firm specialization shows four layers of capability.

- 1 Underpinning infrastructure** C1 and engineering actors provide the operational and environmental base for AD and waste treatment.
- 2 Enabling technologies** C2, C3 and C6 open routes in conversion, gas treatment and CO₂ management.
- 3 GPT-like capabilities** logen, Siemens, EBARA, Alstom and Lummus offer recombinaible industrial competences.
- 4 Complementary domains** C4, C8 and peripheral clusters close loops and connect residues to adjacent applications.

Publication-ready conclusion: the biogas technological system is not a single homogeneous field. It combines infrastructure, conversion routes, gas upgrading, residue valorization and cross-sector industrial capabilities.