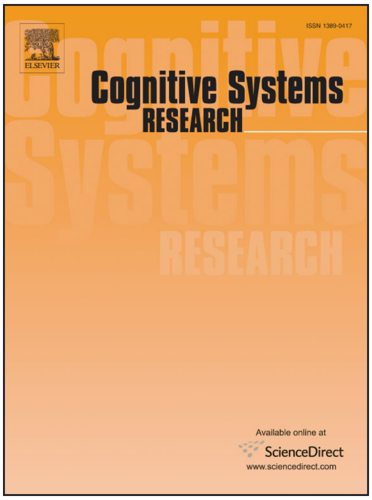

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Systemic Synthetic Modelling:
On a Gaian Reformulation

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Systemic Synthetic Modelling:
On a Gaian Reformulation

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Abstract

The synthetic approach, grounded in the principle of *understanding by building*, has long functioned as a distinctive mode of inquiry across the sciences of the artificial, from cybernetics and artificial life to robotics and synthetic biology. In this context, the construction of software, hardware, and wetware systems that model living and cognitive processes is inseparable from the production of engineering artefacts, so that epistemic exploration and technological development unfold together.

Despite its sustained success, under contemporary conditions this coupled mode of inquiry raises new questions concerning the scale and scope at which synthetic systems are constructed, embedded, and evaluated. As these systems increasingly diffuse and operate in real-world settings, beyond bounded experimental research contexts, the criteria by which they are delimited and assessed become inadequate, calling for a reformulation of the synthetic cycle in relation to extended socio-techno-ecological configurations.

This paper addresses this shift as an internal epistemological problem for the synthetic approach. It proposes a reorientation of synthetic modelling drawing on Gaia theory, understood as a scientific framework that conceptualizes viability as the outcome of distributed regulation in coupled systems operating under bounded material and energetic conditions. On this basis, the paper contributes (i) an epistemological reframing of synthetic modelling under conditions of extended coupling and (ii) a Gaian reformulation of the synthetic cycle oriented to distributed regulation and viability, illustrated through (iii) the introduction of *techno-apoptosis*, originally proposed by [Blinded] and re-articulated here as a Gaian synthetic modelling principle for making artefact lifecycle limits experimentally tractable in robotics.

Keywords: synthetic modelling;synthetic epistemology; Gaia theory; systemic viability; techno-apoptosis; robotics epistemology

1. Introduction

The “synthetic approach” designates a family of research procedures organized around a methodological principle often formulated as “understanding by building” (e.g., Pfeifer & Scheier, 1999). Within this approach, complex natural processes are investigated by constructing artefacts that operationalize explicit scientific hypotheses about the generative mechanisms underlying the target processes. These synthetic systems — software, hardware, or wetware artefacts — are built to instantiate candidate organizational principles and to generate target dynamics under specified constraints. In this sense, they function as epistemic artefacts: experimental constructions through which hypotheses are operationalized, tested, and iteratively revised.

From its early articulations in (proto-)cybernetics to contemporary developments across the sciences of the artificial (Simon, 1968; Blinded), this approach has found privileged objects in life and cognition, where the explanatory adequacy of purely analytic strategies is limited by system-level properties, circular causality, and situated interaction. In research domains such as artificial intelligence, robotics, artificial life, and synthetic biology, synthetic modelling has proven productive in two intertwined directions: it has supported (i) the experimental investigation of generative conditions underlying living and cognitive processes and (ii) the stabilization of technological lineages grounded in that experimental understanding. Today, nearly a century after its first systematic formulations, the synthetic approach is widely recognized as an expanding and influential mode of inquiry.

This paper investigates the synthetic approach at a moment of epistemological transition. Its starting point is the recognition that the synthetic approach is currently subjected to a stress test that brings into question a central feature of its inherited epistemological framing: the treatment of the constructed artefact — defined and evaluated within a circumscribed task setting — as the primary locus of inquiry and of success criteria. This framing is not problematic in itself. It has historically enabled the operationalization and experimental control of generative hypotheses within bounded and experimentally delimited interactional environments.

However, it presupposes that the relevant regime of interaction is adequately captured within the setting where the artefact is constructed and assessed. The difficulty arises when synthetic systems proliferate beyond such controlled contexts and persist as components of extended socio-techno-ecological configurations. Under these conditions, the regime of coupling changes qualitatively. Synthetic systems become materially embedded and temporally extended elements of hybrid configurations, entangled with energy provision, maintenance infrastructures, supply chains, standards, repair and reuse pathways, and end-of-use practices. Criteria of adequacy tied to the original task setting risk becoming epistemically insufficient once operational consequences and dependencies unfold across infrastructures and over time.

This mismatch between bounded experimental framing and extended coupling regimes is the focus of this paper. We treat it as an epistemic problem internal to synthetic modelling: in current conditions of technological diffusion, the inherited framing of synthetic inquiry becomes inadequate as a basis for evaluation once artificial systems operate within extended socio-techno-ecological configurations and along temporally extended trajectories.

In this sense, sustainability does not enter synthetic inquiry as an external normative requirement or a downstream design constraint. It becomes epistemically relevant because extended coupling relations and lifecycle trajectories directly affect what counts as an adequate synthetic model — how models are delimited, how their success is assessed, and how their epistemic yield is interpreted once effects and dependencies unfold across infrastructures and over time.

Within this problem space, the paper advances a Gaian reformulation of the synthetic approach: a reorientation of synthetic modelling in which the scale of construction, embedding, and evaluation is reformulated in relation to extended coupling relations, co-regulatory dynamics, and temporal viability. This reorientation is developed as an epistemological and methodological contribution within the epistemology of synthetic modelling, clarifying how the generative logic of understanding by building must be reformulated under contemporary conditions.

The paper articulates this contribution through three main moves and related contributions: (a) it reconstructs key epistemological commitments of the synthetic approach and identifies their limits in light of extended coupling regimes; (b) it develops a Gaian reformulation of the synthetic cycle, in which construction, embedding, and evaluation are explicitly oriented to regulatory relations and systemic viability; and (c) it introduces an illustrative Gaian modelling principle for robotic research, namely “techno-apoptosis” (Blinded), presented through exemplars that show how lifecycle limits can be made experimentally tractable within regulation-oriented synthetic inquiry.

The paper is organized as follows. *Section 2* clarifies the epistemological stance of the contribution and formulates the research questions, specifying how sustainability is treated here as an epistemic condition of synthetic inquiry. *Section 3* reconstructs the emergence of synthetic modelling and its constructivist logic of *understanding by building*. *Section 4* develops the heuristic of the possible and the interactionist engagement of the synthetic approach, identifying the limits of locally bounded synthetic contexts once synthetic systems are integrated in extended regimes of coupling. *Section 5* introduces the Gaian reformulation and proposes a Gaian synthetic cycle oriented to regulation under Earth-system constraints. *Section 6* develops techno-apoptosis as a modelling operator and presents two exemplars to show how lifecycle limits can be made experimentally tractable within regulation-oriented synthetic inquiry. *Section 7* reframes sustainability as a property of regulatory configurations rather than of individual artefacts. *Section 8* summarizes the methodological commitments implied by this reorientation. *Section 9* concludes by discussing broader implications and future research trajectories.

2. Epistemological and Theoretical Framework

2.1 Scope and epistemological stance

This paper advances an epistemological and methodological contribution to the sciences of the artificial within the field of the epistemology of synthetic modelling, understood as an inquiry into the conditions of possibility, limits, and epistemic yield of the synthetic approach. The latter is construed here as a family of model-based scientific strategies in which hypotheses about natural processes are investigated through the construction and experimental exploration of functioning artificial systems (e.g., Blinded). In this context, artificial models function as epistemic artefacts because they incorporate hypotheses about the generation of target processes and render them experimentally tractable by producing phenomena under specified constraints (Cordeschi, 2002).

The paper analyzes how the synthetic approach can be reoriented when confronted with the stress test introduced in *Section 1*. It does not propose new experimental data or technical prototypes, nor does it aim at a comprehensive historical reconstruction of the sciences of the artificial. Rather, it seeks to clarify how understanding by building operates as an epistemic logic within these sciences and how this logic may require reformulation under contemporary conditions.

A limited history-of-ideas dimension is mobilized to support this inquiry. References to proto-cybernetics, cybernetics, artificial life, and robotics are employed to trace how core commitments of the synthetic approach — such as construction as inquiry, environmental embedding, and comparative evaluation — have been articulated and transformed across modelling media and research domains. This reconstruction is epistemically relevant because it delineates a trajectory to which the present paper proposes a further development.

Within this framework, and in continuity with the problem space outlined above, sustainability is not treated as an external constraint or normative add-on. It is approached as an epistemic condition that problematizes the criteria of adequacy, validity, and success traditionally associated with synthetic models once artificial systems are conceived as materially embedded, coupled, and temporally extended.

2.2 Epistemology, methodology, and the integration of sustainability

A central claim of this paper is that sustainability-related and ethical implications cannot be adequately treated as post hoc constraints imposed on synthetic research. They emerge from the epistemological and methodological commitments that structure synthetic modelling itself. For this reason, the paper does not propose a normative ethical framework for artificial systems, nor does it introduce sustainability as an independent evaluative criterion. Its focus remains epistemological: it examines how specific ways of modelling, constructing, embedding, and evaluating artificial systems shape the space of technological trajectories and systemic consequences that synthetic research makes possible.

From this perspective, epistemological assumptions — such as treating artificial systems as delimited units within bounded regimes of interaction, privileging performance optimization, or presupposing open-ended persistence — are not neutral with respect to sustainability and ethics. They condition what kinds of artefacts are produced, how these artefacts are situated within their environments, and how their lifecycle dynamics unfold across infrastructures and over time. Sustainability-related issues thus become epistemically visible when artificial systems are conceived as materially embedded, resource-dependent, and temporally finite components of broader socio-technical and ecological configurations (e.g., Blinded; Blinded).

The contribution of this paper lies in making this structural relation explicit. By developing an epistemology of synthetic modelling, it shows how sustainability can be understood as an epistemic condition of inquiry under contemporary conditions of large-scale technological diffusion and ecological constraint. The question, therefore, is not whether sustainability considerations should be added to synthetic research, but how the generative logic of understanding by building must be reformulated once artificial systems are recognized as participants in coupled, resource-bounded, and temporally extended regulatory configurations. Under these conditions, the criteria of adequacy, validity, and epistemic relevance that traditionally guide synthetic modelling are themselves called into question.

2.3 Gaia theory as a systemic reference for synthetic modelling

To articulate the epistemological reorientation outlined in the previous sub-section, the paper adopts a Gaian framework as its theoretical reference, situated within a broader systemic understanding of sustainability. Gaia is not invoked as metaphor, teleology, or moral principle. It functions here as a scientific framework for analysing the conditions under which complex, coupled systems remain viable over time under bounded material and energetic constraints.

Originally formulated by James Lovelock in the late 1960s and early 1970s, and further developed in dialogue with Lynn Margulis, the Gaia hypothesis proposed that life and its physical environment form a tightly coupled system in which biological, chemical, and geological processes co-evolve through distributed regulatory dynamics (Lovelock, 1979; Lovelock & Margulis, 1974). While early interpretations occasionally framed Gaia in organismic terms, subsequent developments progressively integrated the hypothesis within systems theory, feedback regulation, and Earth System Science (e.g., Boston & Schneider, 1993; Lenton & Latour, 2018).

In its contemporary scientific articulation within Earth System Science, Gaia does not describe the Earth as a super-organism, nor does it posit intentional regulation. Rather, it provides a framework for understanding how large-scale viability emerges from the interaction of heterogeneous processes operating under biophysical constraints. Planetary regulation is conceived as historically contingent, distributed, and non-linear, arising from the coupling of life processes, geophysical dynamics, and material flows rather than from centralized control (Lenton & Latour, 2018; Rubin et al., 2021; Lenton, 2025).

Within this framework, sustainability is understood in systemic terms. It concerns the capacity of coupled systems to maintain viable modes of operation under bounded material, energetic, and organizational conditions. When considered from the standpoint of the sciences of the artificial, this implies that artificial systems cannot be adequately analysed as relatively self-contained artefacts. Their operation, persistence, degradation, and transformation are inseparable from the socio-techno-ecological configurations in which they are materially embedded.

Adopting a Gaian framework here does not amount to deriving normative prescriptions from ecological models. Rather, Gaia functions as a theoretical basis for identifying which dimensions of artificial systems become epistemically relevant when synthetic modelling is conducted under conditions of extended coupling and systemic constraint. In this sense, the Gaian reformulation proposed in this paper is an epistemological reorientation. It reframes the criteria by which synthetic models are conceptually delimited and epistemically evaluated, shifting attention from isolated performance and task-specific adequacy toward systemic integration, regulatory participation, and temporal viability within hybrid socio-techno-ecological configurations.

2.4 Focus and research questions

Within the broad landscape of the sciences of the artificial, this paper focuses primarily on research trajectories in robotics articulated through the synthetic approach. This choice is motivated by the epistemological role that robotics plays within synthetic modelling. Robotic systems instantiate *understanding by building* in a particularly concrete and demanding form; they are embodied artefacts that operate in physical environments, unfold over extended lifecycles, and interact continuously with social, technical, and ecological infrastructures. On these grounds, robotics provides a privileged domain for analysing how synthetic models transition from experimental constructions to integrated components in real-world configurations.

This focus follows directly from the Gaian framework introduced in the previous sub-section. When synthetic modelling is conducted under conditions of systemic coupling and sustainability, questions of material embedding, persistence, degradation, and withdrawal become epistemically central. Robotics foregrounds these dimensions more explicitly than modelling paradigms in which material embedding and lifecycle trajectories are less immediately visible. For this reason, the paper does not address artificial intelligence as an abstract computational paradigm, nor does it focus on disembodied algorithmic systems such as Large Language Models. The emphasis is instead on situated artificial systems whose embodiment, materiality, and lifecycle trajectories render issues of systemic integration and temporal viability unavoidable.

Based on this background, the paper is guided by the following research questions.

RQ1. *How can the synthetic approach, grounded in* understanding by building*, be reoriented when artificial systems are conceived as ecologically embedded components rather than as units whose adequacy is assessed within circumscribed task settings?*

RQ2. *What changes in the principles and evaluation criteria of synthetic modelling follow from adopting a systemic Gaian perspective that foregrounds coupling, bounded resources, and long-term viability?*

RQ3. *How can techno-apoptosis function as a synthetic modelling principle through which lifecycle limits, transformation, and withdrawal become experimentally accessible dimensions of synthetic inquiry?*

These questions are analytically distinct but epistemologically entangled. Together, they articulate a reconfiguration of synthetic modelling in which epistemological assumptions, methodological principles, modelling operators and theoretical constructs co-evolve under conditions of systemic coupling and sustainability.

3. The Emergence and Evolution of Synthetic Modelling

3.1 Building a Synthetic Epistemology on "Machines that Think"

The reorientation of synthetic modelling under contemporary sustainability conditions places under stress a mode of inquiry whose methodological and epistemological core was established at the very origins of the sciences of the artificial. Recalling its main developments serves to identify the epistemic logic of synthetic modelling that will later be put under stress by extended coupling regimes and reformulated under Gaian constraints.

Born in the early twentieth century at the intersection of engineering, biology, and experimental psychology, what later came to be known as "the synthetic method" marked a turning point in the scientific study of life and cognition. Its origins can be traced to what Roberto Cordeschi (2002) has described as "proto-cybernetics": an exploratory research tradition that laid the epistemological and methodological foundations of the cybernetic movement. Key figures in this context include John Hammond Jr., Benjamin Miessner, Bent Russell, and Jacques Loeb, whose experimental work involved the construction of artificial devices — such as the well-known *electric dog* — inspired by Loeb's theory of tropisms.

Importantly, these machines were not conceived as metaphors or illustrative models, but as experimental artefacts designed to operationalize theoretical hypotheses in behavioral biology. Their epistemic function was not to reproduce biological structures, but to render experimentally tractable questions concerning organization, regulation, and behavior. The guiding intuition was that constructing an artificial system capable of exhibiting a target behavior could provide insight into the generative conditions underlying that behavior in nature. In this sense, the core idea of synthetic modelling was already clearly articulated: to build in order to understand.

One of the earliest and most explicit formulations of this strategy appears in the work of engineer Thomas Ross. In a series of papers published in the 1930s, Ross designed and experimentally explored electromechanical "learning machines", most notably maze-solving devices inspired by behaviorist theories of learning. In his 1933 *Scientific American* article, Ross famously described these devices as "machines that think", and explicitly introduced the term *synthetic method* to characterize this experimental strategy (Ross, 1933). Crucially, Ross framed the synthetic method as a test of epistemic sufficiency. As he later stated with particular clarity:

> "One way to be relatively sure of understanding a mechanism is to make that mechanism. To find the sufficient conditions for learning we should try to make a machine that will learn." (Ross, 1938, p.185)

The aim of the synthetic method, in this formulation, was not to answer the question of what cognition *is*, but to investigate which organizational conditions are *sufficient* to generate observable cognitive-like behavior. Ross repeatedly emphasized that the successful performance of an artificial system demonstrates the possibility of a given functional organization, not its exclusivity. As he wrote:

> “What is demonstrated by the physical existence of a performing machine is that a machine is capable of that kind of performance. It is not demonstrated, however, that only this sort of machine can produce the given effects.” (Ross, 1938, p.185)

Ross’s work thus anticipated several key commitments of later synthetic modelling. First, it established the construction of material artefacts as a legitimate mode of scientific inquiry. Second, it treated artificial systems as epistemic artefacts: devices built to embody and test hypotheses about the generative mechanisms of natural processes. Third, it grounded evaluation not in structural imitation, but in functional performance under experimentally controlled conditions.

From an epistemological standpoint, Ross’s contribution foreshadowed two diverging yet coexisting trajectories within synthetic modelling. On the one hand, it supported a functionalist logic of multiple realizability, according to which cognitive and biological functions can be instantiated across heterogeneous material substrates. On the other hand, it opened the way to an emergentist perspective emphasizing the inseparability of cognitive processes from the material, organizational, and environmental conditions through which they arise. Importantly, this tension was not resolved at the level of explicit theory, but enacted and explored within early synthetic practices themselves, through experimental constructions that tested functional sufficiency while remaining materially and organizationally situated (e.g., Cordeschi, 2002, 2006).

Building on Ross’s experimental strategy and related proto-cybernetic work, cybernetics progressively extended the synthetic method — first conceptually, then operationally — through computational, electromechanical, and later chemical implementations — in software, hardware and wetware artefacts (e.g., Rosenblueth et al. 1943; Bedau, 2003). This historical development gave rise to what is now commonly referred to as the *synthetic approach*: a cross-disciplinary, cross-media methodological orientation grounded in the principle of *understanding by building*. The synthetic approach cuts across artificial intelligence, artificial life, robotics, and synthetic biology, preserving a common epistemic logic while adapting to diverse modelling media and experimental contexts (e.g., Blinded).

The progressive consolidation of this approach marks the emergence of what can be described as a *synthetic epistemology*: a mode of scientific inquiry in which construction, experimentation, and theoretical reflection are tightly intertwined, and in which artificial systems function as generators of phenomena rather than as passive representations of pre-given objects.

3.2 The Synthetic Approach as a Constructivist Inquiry

In the foundational phase of cybernetics, the epistemological significance of the synthetic approach was articulated with increasing methodological clarity. A schematic reconstruction of this phase provides the epistemic baseline against which the limits of locally bounded modelling contexts will later be assessed.

Figures such as Kenneth Craik (1943), Warren McCulloch and Walter Pitts (1943), and Arturo Rosenblueth, Norbert Wiener, and Julian Bigelow (1943) explicitly framed synthetic modelling as a necessary complement to the classical analytical method of scientific rationality. Whereas the analytical approach proceeds by decomposition and abstraction, aiming to isolate elementary components and laws, the synthetic approach builds operational systems to investigate complex, emergent dynamics (e.g., Simon, 1968). Importantly, this shift does not reject analysis, but complements its role through an epistemic endeavour oriented toward construction, exploration, and experimental feedback. Synthetic modelling thus becomes a means of testing the sufficiency of, and refining theoretical assumptions by embedding them in functioning artefacts capable of artificially (re-)generating target observable phenomena.

These cybernetic contributions did not merely legitimize synthetic modelling as a scientific practice; they also sharpened its operational structure. In continuity with proto-cybernetic explorations, cybernetics articulated a more explicit methodological cycle that continues to inform contemporary synthetic research. This cycle can be schematically described in three interrelated phases.

1. *Construction*: the design and implementation of an artificial system capable of synthetically generating the processes under investigation, based on explicit hypotheses about their generative mechanisms.
2. *Environmental Embedment*: the integration of the artificial system within a natural, artificial, or hybrid environment consistent with the theoretical framework, enabling system–environment interactions through which target dynamics can emerge.
3. *Comparative Evaluation*: the assessment of the artificial system's behavior in relation to its natural counterpart, in order to evaluate the operational adequacy and explanatory power of the initial hypotheses (e.g., Blinded).

Divergences between artificial and natural dynamics are not treated as experimental failures, but as diagnostically productive mismatches. When such divergences cannot be attributed to contingent material limitations, they are interpreted as signals of insufficiencies in the underlying hypotheses, prompting their revision or broader theoretical reformulation. This diagnostic process thus initiates a potentially open-ended iteration of hypothesis implementation and reformulation; a recursive process that reflects the epistemic status of the target systems addressed by synthetic modelling.

Living and cognitive systems are not "trivial" objects for the observer (von Foerster, 2003). Their behaviour is not a linear reaction chain that can be exhaustively inferred from external inputs. In these systems, external pressures trigger endogenous processes of regulation: self-regulatory dynamics that depend on the system's organization, structure, and history of interaction. For this reason, such systems resist not only environmental pressures but also experimental manipulation (e.g., Stengers, 1985).

On these grounds, living and cognitive systems exceed forms of scientific understanding that rely primarily on prediction and experimental control (e.g., Maturana & Varela, 1987; Ceruti, 1994). To proceed, their exploration can attempt material construction. Synthetic modelling —

understanding by building — operationalizes this epistemological choice by implementing hypothesized generative mechanisms in artificial systems and exploring them in situated experimental conditions, so that the relevant dynamics can be produced and iteratively re-specified.

Synthetic intelligibility is therefore an intelligibility of construction. The observer is not a neutral spectator but an active maker of the experimental object and of the conditions under which phenomena become accessible. The epistemological space of synthetic inquiry is not structured by classical oppositions (facts vs. artefacts, discovery vs. invention, representation vs. construction) but by their complementarity. In synthetic practice, what counts as an accessible *fact* is inseparable from the *artefact* that makes it observable, and the discovery of a mechanism coincides with its operational invention (Blinded). By embedding principles such as emergence, self-regulation, and circular causality into material implementations, synthetic artefacts can generate behaviours not fully anticipated at the design stage. In Pickering's sense, they function as "revealing machines": constructed systems capable of surprising their creators and reorganizing theoretical expectations (Pickering, 2010). Synthetic epistemology thus turns limits of intelligibility into sites of epistemic productivity; an epistemological configuration that will be put under pressure by contemporary sustainability constraints, motivating the reorientation developed in the following section. What remains implicit in this epistemology is the assumption that the relevant regime of system–environment coupling can be adequately delimited at the scale of experimental construction and evaluation — an assumption that will be critically re-examined in the following sections.

4. From Plural Realizations to Systemic Entanglements: Limits of Local Interactionism in the Synthetic Approach

4.1 The Heuristic of the Possible: Structural Pluralism in Synthetic Modelling

A key epistemic strategy of synthetic modelling can be defined as a *heuristic of the possible*. Synthetic inquiry does not ask only how a target process works as it is, but also why it takes one form rather than another, by constructing and exploring alternative realizations of candidate generative hypotheses (e.g., Luisi, 2006). This orientation has characterized the synthetic approach to life and cognition since its early formulations: the attempt to develop a general science of life and cognition by studying not only how living and cognitive processes and systems are, but also how "they could be" (e.g., Langton, 1989; Brooks, 1999; Cavalli et al., 2025).

This pluralism is not merely a heuristic preference. It is structurally entailed by the epistemic conditions of synthetic modelling. Any synthetic model of a target phenomenon is the outcome of a chain of unavoidable decisions: (i) the selection of a theoretical hypothesis, (ii) its operational interpretation, (iii) a choice of abstraction level, (iv) the selection of an implementation medium (computational, electromechanical, biochemical), and (v) design decisions imposed by the constraints of making the system operational. Each step introduces alternatives; each alternative generates non-equivalent realizations. A synthetic model therefore never coincides with the "real thing", but with a situated synthetic interpretation of a target process — one among several possible, and always constrained by conditions of implementation (Blinded).

For this reason, synthetic modelling cannot be framed as a choice between pure imitation and full reproduction, as suggested by certain Searlean-like dichotomies in ALife and AI debates. On the one hand, mere imitative proximity may remain epistemically shallow, preserving surface similarity without discriminating generative mechanisms. On the other hand, "complete reproduction" is not only impractical but conceptually misguided, since synthetic models are built within an experimental reach that requires simplification, controlled conditions, and bounded variability. A broad and productive space therefore lies between imitation and reproduction, structured by comparative exploration of alternative realizations.

What makes this intermediate space scientifically productive is that it allows systematic comparison among implementations, in order to probe what a given hypothesis can and cannot generate under different media, constraints, and design configurations, within bounded experimental settings (Blinded).

This structural pluralism is generative in two tightly coupled senses. Scientifically, it enlarges the experimental workspace within which candidate operational principles of life and cognition can be stress-tested across heterogeneous realizations. Technologically, it supports the progressive stabilization of such realizations as artificial systems — implemented across software, hardware, and wetware lineages — that are eventually deployed beyond controlled laboratory settings.

4.2 Structural Interactionism: From Plural Realizations to Plural Couplings

The structural pluralism described above does not concern alternative implementations of supposedly internal mechanisms only. It extends to the relational conditions under which target behaviours are generated. From its articulation in ALife (Langton, 1989) to its development in embodied and evolutionary robotics (e.g., Brooks, 1991; Pfeifer & Bongard, 2007; Doncieux et al., 2015), the synthetic approach has been increasingly grounded in an interactionist hypothesis: synthetic models are not designed to generate behaviours in isolation. Target dynamics are treated as outcomes of distributed couplings among systems, components, and environments.

This point matters epistemologically. In synthetic inquiry, the relevant question is not how a pre-given system "internally" produces behaviour, but how multiple organisational levels — system, its subsystems, and environment — jointly generate viable dynamics. In this sense, the heuristic of the possible presupposes an *ecology of possible couplings*, not only a space of alternative internal designs. Different realizations of a hypothesis entail different constraints, interfaces, and regimes of interaction; the implementation of these alternatives conditions the range of dynamics that the model can exhibit. In synthetic practice, what is constructed is therefore not an artefact in isolation, but a "model-environment supersystem": an experimentally configured *synthetic ecology* within which perturbations, viable responses, and behavioural trajectories are made accessible by design decisions (Blinded).

This interactionist configuration is already implicit in the methodological cycle described in *Section 3*: construction is inseparable from environmental embedding, and evaluation presupposes situated coupling. Synthetic inquiry operationalizes principles such as self-regulation, circular causality, and emergent dynamics as relational processes unfolding within bounded experimental ecologies, rather than as properties of isolated mechanisms.

This is where a critical limitation begins to take shape. These ecologies remain engineered and circumscribed. The relevant couplings are selected, constrained, and stabilized to render the dynamics under investigation experimentally tractable. Interactionism is structurally present, but locally framed — interaction under experimentally delimited regimes of coupling. It is precisely this locality that becomes critical when synthetic realizations scale beyond experimental settings.

4.3 Robotics and the materialization of synthetic interactionism

Among the domains shaped by the synthetic approach, robotics renders the interactionist logic of synthetic modelling particularly explicit by requiring synthetic models to persist materially and operate in situated physical conditions. In embodied robotics, behaviour is not explained by control alone: it arises from sensory–motor coordination achieved through a "subtle interplay" of morphology, materials, control, and interaction with the environment (e.g., Pfeifer & Iida, 2004). On this view, what appears as cognitive behaviour is not primarily a property of an internal computational core, but a consequence of how control tasks are distributed across body dynamics, material properties, sensorimotor loops, and environmental structure—an idea formalized in the embodied AI principle of ecological balance (e.g., Pfeifer & Scheier, 1999).

This is also why robotics provides a natural bridge between the synthetic approach and the interactionist commitments of artificial life. Population-based and multi-agent traditions emphasize how complex global patterns arise from simple rules and local interactions, reframing the unit of analysis from the individual agent to the coupled dynamics of many components and their environment (e.g., Brambilla et al., 2013; Doncieux et al., 2015). In parallel, evolutionary and swarm robotics foreground how self-organization and distributed intelligence arise from local interactions, while soft and morphological robotics investigate how physical structure and material properties shape behaviour (e.g., Laschi et al., 2016). Beyond electromechanical embodiments, emerging directions in chemical robotics extend this logic to molecular and prebiotic domains, in which regulation and adaptive dynamics are explored through forms of chemical self-organization (e.g., Stano, 2023; Blinded).

Across these trajectories, robotics appears less as a technology than as a synthetic mode of inquiry into embodied and ecologically embedded cognition across heterogeneous substrates.

Epistemologically, robotics sharpens a point that can remain partially implicit in purely computational modelling. Synthetic systems persist in physical environments, unfold over time, consume resources, and undergo wear, drift, repair, and failure. Their behaviour is therefore inseparable from material embedding and environmental constraint. In this sense, robotics makes explicit that synthetic models and artificial systems operate as components of situated ecologies, whose capacities are co-determined by the regimes of coupling in which they are embedded.

4.4 From bounded synthetic ecologies to extended socio-techno-ecological couplings

In making explicit the interactionism underlying synthetic modelling and its technological production, robotics also exposes its structural fragility.

In laboratory practice, couplings are engineered. Tasks, environments, and evaluation protocols are designed so that relevant dynamics can be observed and compared. Even when behaviour appears open-ended, it is open-ended within an ecology whose boundaries, resources, and interfaces are experimentally defined. When robotic and synthetic realizations migrate into technological infrastructures, their interaction regime changes qualitatively. Systems originally studied within locally engineered synthetic ecologies become embedded in wider socio-techno-ecological networks. Their couplings extend beyond the experimental frame, intersecting with material flows, maintenance infrastructures, institutional constraints, economic circuits, and ecological conditions that exceed the original modelling assumptions. Yet the epistemological stance inherited from laboratory modelling can continue — implicitly — to treat relevant interactions as if they remained local and containable. For instance, a system evaluated as successful within a bounded task environment may generate unforeseen material and infrastructural dependencies once deployed at scale.

This mismatch is where the sustainability problem becomes relevant in synthetic modelling. The same interactionist logic that enables complex behaviour under controlled conditions becomes insufficient when artificial systems are integrated in extended regimes of coupling and constraint. As anticipated, what is at stake is not an added ethical layer, but the adequacy of the synthetic framing itself: whether the criteria of success, validity, and relevance — developed for bounded experimental ecologies — remain defensible once synthetic systems are understood as materially embedded participants in extended hybrid configurations.

This is the point at which a Gaian framework becomes methodologically pertinent. It provides a way to reframe sustainability as a condition of systemic viability under coupled, multi-scale constraints, rather than as a set of local design requirements applied to isolated artefacts. It offers what is needed: not a local redesign of artefacts, but a re-specification of the scale at which regulation is conceptualized.

5. The Gaian Turn: Reframing the Synthetic Approach under Earth-System Constraints

5.1 From Homeostatic Gaia to Earth-System Dynamics

The Gaia hypothesis was initially formulated by James Lovelock and later developed with Lynn Margulis as a proposal about the Earth's capacity to maintain conditions conducive to life through coupled interactions between biological and physico-chemical processes (Lovelock & Margulis, 1974; Lovelock, 1979). In its early articulation, Gaia was primarily associated with homeostasis: global variables such as atmospheric composition and temperature were treated as outcomes of distributed feedback mechanisms in which living organisms play a constitutive regulatory role.

From the beginning, this perspective was compatible with cybernetic concerns, insofar as regulation through feedback could be conceptualized without centralized control (e.g., Andrew, 1996). Yet the Gaian programme progressively expanded beyond a homeostasis-as-equilibrium picture, moving toward a complex-systems understanding of Earth dynamics: regulation as historically contingent, multi-scale, and dynamically maintained under perturbation rather than as a fixed steady state (Onori & Visconti, 2012; Lenton & Latour, 2018).

In contemporary debates, this evolution also includes attempts to reconcile Gaian frameworks with evolutionary theory, rethinking the conditions under which planetary-scale persistence and regulation can be conceptualized without invoking teleological claims (Doolittle, 2024).

What matters for our purposes is the epistemological shift. Gaia increasingly functions as a way to conceptualize viability as a property of coupled regulation across scales; therefore raising, for the sciences of the artificial, the question of how regulation is modelled, delimited, and evaluated.

5.2 Cybernetics: Regulation, Observation, and Synthetic Ecologies

This Gaian trajectory can be clarified by recalling the original problem that defined cybernetics: regulation. From its inception, cybernetics addressed the question of how complex systems maintain stability, coordination, and viability under changing conditions.

Within the context of "first-order cybernetics", in the work of pioneers such as Norbert Wiener, Arturo Rosenblueth, and Ross Ashby, regulation is analysed from the standpoint of an external observer modelling an observed system. Feedback mechanisms are described as organizational arrangements that stabilize selected variables within defined boundaries. Regulation, in this sense, concerns the maintenance of operational coherence relative to specified constraint (e.g., Novikov, 2015)

However, this formulation presupposes that system boundaries, relevant variables, and evaluation criteria are already given. "Second-order cybernetics", as proposed by Heinz von Foerster (2003) and the BCL research group work, introduced a decisive shift by questioning this presupposition. When observing systems are considered part of the object of analysis, regulation can no longer be treated as an objective property of an independently delimited system. Rather, it is inseparable from the epistemic operations through which system boundaries, perturbations, and viability conditions are specified. The observer becomes part of the regulatory configuration, and regulation is redefined as reflexive: it includes the processes through which it is described, enacted, and evaluated (Umpleby & Medvedeva, 2022).

For the synthetic approach, this distinction is far from being abstract. Synthetic modelling is already an intervention into regulatory dynamics. What is constructed in practice is not an isolated artefact but a bounded model-environment supersystem, or a synthetic ecology, within which regulatory relations are experimentally staged. The modeller does not merely observe regulation, but specifies the variables, constraints, and couplings through which regulation can emerge and be measured. In this sense, synthetic modelling operationalizes a *second-order insight* in material form: regulation is not "discovered in isolation", but enacted within constructed ecologies whose boundaries are epistemically and experimentally defined.

The critical issue arises when these bounded synthetic ecologies intersect with wider socio-techno-ecological aggregations. If regulation is always defined relative to specified boundaries and variables, then the question becomes unavoidable: at what scale is regulation being modelled? And what agent defines the relevant limits of viability? It is precisely this problem of scale and boundary specification that makes the Gaian perspective methodologically relevant in this context.

This scaling problem also resonates with what has been described as "third-order cybernetics", construed as a shift from individual system-observer units to self-developing, reflexive-active environments in which multiple heterogeneous agents participate in shaping the conditions of regulation (Lepskiy, 2018; Espejo & Lepskiy, 2020). In such configurations, regulation can no longer be localized within a single system or fully controlled by a centralized observer. It unfolds within historically evolving socio-techno-ecological configurations whose boundaries are neither fixed nor externally given. The regulatory field itself becomes distributed, dynamic, and co-constituted through ongoing interaction.

The Gaian reformulation of the synthetic approach rearticulates this insight by extending the regulatory horizon to Earth-systemic coupling. What is at stake is not merely the reflexivity of the observer, but the scale at which viability is conceptualized and modelled. In this perspective, regulation must be addressed as a multi-scale, materially constrained process unfolding across nested configurations of coupling.

5.3 From Earth-System Thinking to a Gaian Paradigm of the Synthetic Approach

On these bases, here we use *Gaian* to denote a reorientation of the synthetic approach in which synthetic modelling targets extended regulation as a modelling problem — i.e., as something that must be constructed, delimited, and evaluated within synthetic ecologies under Earth-system constraints. The point is not to assume that technological artefacts are *de facto* beneficial to ecological viability. Rather, the Gaian turn formulates a research problem internal to synthetic epistemology: *under what conditions can artificial systems be designed and studied as integrated components* — participants — *in configurations of co-regulation that remain viable over time?*

Two consequences follow.

First, the epistemic aim of *understanding by building* is reframed in regulatory terms. In classical synthetic practice, behaviour generation designates the capacity of a constructed system to produce relevant dynamics through engineered system–environment couplings within bounded ecologies. Under Gaian constraints, the "target" shifts: what becomes central is whether and how a built system can take part in regulatory couplings that stabilize, transform, or renew broader conditions of viability. Far from being a normative, additional constraint, this is an epistemological expansion of what counts as an adequate synthetic hypothesis. In other words: the hypothesis now concerns not only local dynamics, but also the *regulatory relations* through which the system is maintained, repaired, transformed, or withdrawn across time.

Second, evaluation criteria shift accordingly. In the synthetic approach, divergences between natural and artificial dynamics are epistemically productive because they expose limitations of hypotheses and guide iterative refinement. Under Gaian constraints, this diagnostic function remains central, but the space of divergences expands. It includes mismatches that occur across lifecycle phases and within extended couplings — e.g., dependencies on infrastructures, maintenance regimes, material flows, and institutional practices that condition how regulatory participation is sustained over time. In other terms, the synthetic comparison must be able to register not only behavioural divergence, but also divergence in co-regulatory integration.

5.4 The Gaian Synthetic Cycle

To make this reorientation operational at the level of synthetic practice, we propose a Gaian reformulation of the classical synthetic cycle, which specifies what must be constructed, made explicit, and evaluated when the object of modelling is extended regulation under Earth-system constraints.

(1) Constructive Modelling (regulation-oriented hypotheses). Synthetic systems are designed to instantiate hypotheses about regulatory co-evolution within bounded environments. Architectures operationalize not only hypotheses about local mechanisms, but also hypotheses about how regulatory coupling is sustained over time (e.g., conditions of maintainability, repairability, transformability, and withdrawal as part of systemic continuity).

(2) *Ecological Embedding (coupled constraints made explicit).* Models are embedded in environments in which constraints are not treated as mere background conditions, but as constitutive elements of the regulatory dynamics under investigation. Embedding therefore includes specifying the relevant coupling relations — material, energetic, infrastructural, institutional — through which the system can, or cannot, contribute to co-regulation.

(3) *Systemic Evaluation and Renewal (diagnostic divergences across time).* Evaluation extends beyond local performance to include the system's contribution to, or disruption of, co-regulatory viability over time. Divergences are treated as epistemic evidence not only about internal design limits, but also about tensions in the coupling relations that sustain, or destabilize, regulatory participation — thus guiding renewed iterations of both artefact design and modelling assumptions.

Table 1. *The synthetic approach: classical vs gaian version*

Dimension	**Classical Synthetic Approach**	**Gaian Reorientation of the Synthetic Approach**
Epistemic aim	*Understanding-by-building* locally bounded synthetic systems	*Understanding-by-building* ecologically embedded systems
Model status	Epistemic artefact within bounded synthetic ecologies	Component in hybrid socio-ecological assemblages
Evaluation focus	Task- and ecology-bounded behavioural/functional comparison	Systemic contribution over lifecycle
Treatment of boundedness	Contingent / engineering constraint	Designed and epistemically relevant
Role of sustainability	External norm / design add-on	Internal epistemic condition
View on failure/end-of-life	Failure primarily treated as local malfunction within bounded ecologies	Diagnostic moment within the synthetic cycle

This Gaian cycle provides the epistemological frame for the remainder of the paper. It allows the synthetic approach to treat sustainability as an integrated condition of inquiry, by making regulatory contribution — rather than task- and context-bounded performance — the primary target of construction, embedding, and comparison. Within this framework, specific modelling operators can be introduced to render particular dimensions experimentally tractable. The next section introduces techno-apoptosis as one such operator.

6. Techno-Apoptosis as a Gaian Modelling Principle

6.1 Techno-Apoptosis: From Biological Process to Synthetic Modelling Principle

Within the Gaian reorientation of the synthetic approach, the question of lifecycle limits becomes structurally unavoidable. If synthetic systems are conceived as integrated components in extended configurations of co-regulation, then their persistence, transformation, and withdrawal can no longer be treated as external engineering concerns or downstream sustainability issues. They become intrinsic dimensions of what is being modelled and experimentally explored.

It is in this context that we propose "techno-apoptosis", a notion originally proposed by [Blinded] and here reformulated as a modelling principle within the Gaian synthetic framework. Techno-apoptosis draws inspiration from biological apoptosis, understood not as accidental decay or pathological failure, but as a regulated process through which individual elements contribute to systemic viability through self-elimination. In biological systems, apoptosis supports development, differentiation, and long-term adaptability by preventing uncontrolled accumulation and sustaining organizational coherence (e.g., Elmore, 2007).

Here, techno-apoptosis does not operate as a metaphorical transfer from biology to technology. Rather, it functions as an operative principle: the intentional design of artificial systems whose architectures incorporate conditions for programmed self-dismantling, modular redistribution, and material reintegration. Designed termination is thus treated as a functional and epistemic dimension of synthetic construction. Dismantling and reintegration become experimentally variable components of regulatory participation.

Philosophically, this perspective resonates with approaches that challenge extractive and domination-oriented conceptions of technology. Sloterdijk's distinction between "allotechnics" and "homeotechnics" provides a useful conceptual reference (Sloterdijk & Heinrichs, 2011; van der Hout, 2014; Blinded). Whereas allotechnics frames technology as an external force imposed upon nature, homeotechnics envisions technological practices as structurally aligned with natural processes. The design of systems capable of regulated self-dismantling can be understood as inhabiting ecological logics rather than overriding them.

Morin's socio-philosophical interpretation of apoptosis as functional sacrifice further clarifies the point (Morin, 1999). Local disappearance can enable systemic continuity. Techno-apoptosis extends this insight into synthetic modelling by treating programmed withdrawal not as failure, but as a potential mode of regulatory participation. In this way, techno-apoptosis provides one specific modelling articulation to the Gaian framework, through which lifecycle transitions become experimentally tractable within regulation-oriented synthetic inquiry.

Table 2. *Apoptosis and techno-apoptosis within the Gaian synthetic approach*

Aspect	***Biological Apoptosis***	***Techno-Apoptosis***
Status	Natural biological process	Synthetic modelling principle
Function	Systemic viability through regulated elimination	Systemic viability through designed termination and reintegration
Trigger	Developmental / regulatory signals	Condition-based design thresholds
Epistemic role	Object of exploration	Experimental modelling variable
Sustainability relevance	Contributes to long-term systemic viability	Makes lifecycle termination and reintegration experimentally tractable within regulatory modelling

6.2 Techno-Apoptotic Scenarios as Synthetic Modelling Exemplars

To clarify how techno-apoptosis can function within synthetic inquiry, we introduce two modelling exemplars. These scenarios are not engineering forecasts, but epistemic constructions; experimental spaces in which lifecycle limits can be treated as a variable within the Gaian synthetic cycle outlined in *Section 5.4.*

6.2.1 Electromechanical Scenario: Distributed Dismantling in Robotic Ecologies

Consider an urban service ecology populated by autonomous robotic units operating across interconnected homes, streets, and service infrastructures. Units monitor operational parameters (e.g., energy efficiency, sensor reliability, maintenance load, material wear) and exchange information within the network.

In a techno-apoptotic configuration, degradation beyond specified thresholds activates coordinated dismantling at the level of the robotic ecology rather than isolated failure or external disposal. Neighbouring units initiate structured disassembly through which recoverable components are catalogued, refurbished, and redistributed via designed reuse pathways.

Dismantling thus functions as a regulatory operation within the synthetic ecology: selective local withdrawal supports collective viability by preventing accumulation and sustaining operational capacity across time. Analogous forms of regulated elimination in eusocial organisms (e.g., *Apis mellifera*; Ihle et al., 2022) illustrate how local loss can contribute to systemic coherence, without implying biological equivalence.

From a synthetic epistemological perspective, this scenario renders tractable degradation thresholds, modularity, redistribution rules, and criteria of systemic contribution, positioning techno-apoptosis as a modelling operator for investigating designed withdrawal and transformation rather than indefinite persistence.

6.2.2 Wetware Scenario: Programmed Dissolution and Ecological Reintegration

A parallel articulation can be explored in wetware and synthetic biology through programmable protocells designed for catalytic remediation in polluted aquatic environments.

In a techno-apoptotic configuration, once remediation thresholds are reached or temporal windows expire, protocells initiate programmed dissolution. This extends early proposals for self-demolishing synthetic cells in nanomedicine (e.g., LeDuc et al., 2007) into an explicitly ecological modelling framework. Breakdown products are designed to be biocompatible and reintegrable into existing ecological cycles, functioning as nutrients or molecular precursors for further chemical self-organization.

Here, viability is decoupled from persistence: success is indexed to contribution followed by residue-free or regenerative withdrawal. Dissolution rates, by-product composition, uptake pathways, and systemic effects become experimentally tractable dimensions, positioning techno-apoptosis as a modelling operator for articulating contribution, withdrawal, and reintegration as phases of a regulatory trajectory rather than as endpoints of functional breakdown.

Table 3. *Techno-apoptosis: electromechanical vs wetware exemplars*

Dimension	***Electromechanical scenario***	***Wetware scenario***
Techno-apoptotic operator	Coordinated dismantling and redistribution	Programmed dissolution and reintegration

Dimension	*Electromechanical scenario*	*Wetware scenario*
Regulatory function	Collective viability through component circulation	Ecological viability through biocompatible breakdown
Lifecycle phase modelled	End-of-life as systemic resource	End-of-function as ecological contribution
Experimentally tractable variables	Degradation thresholds; modularity; redistribution rules; systemic contribution	Dissolution rates; by-product composition; uptake pathways; systemic effects
Epistemic function	Model withdrawal as regulatory contribution	Model reintegration as regulatory contribution

6.3 Techno-Apoptosis within Third-Order Configurations

The epistemological relevance of techno-apoptosis becomes clearer when situated within a third-order cybernetic perspective. In first-order cybernetics, regulation is analysed from the standpoint of an external observer; in second-order cybernetics, reflexivity emerges through inclusion of the observer within the system of regulation. Third-order cybernetics shifts attention further, toward distributed networks of interacting agents embedded in self-developing environments (e.g., Novikov, 2015; Lepskiy, 2018; Espejo & Lepskiy, 2020).

In such socio-techno-ecological contexts, environments are not passive backgrounds, but evolving configurations co-shaped by heterogeneous agents — human, artificial, institutional, infrastructural, ecological; and regulation is distributed across these systems, where unfolds historically.

When introduced within the Gaian synthetic cycle (*Section 5.4*), techno-apoptosis modulates each phase. At the constructive stage, lifecycle limits become part of the regulatory hypothesis instantiated by design. Architectures incorporate thresholds, modular reversibility, and conditions of withdrawal as variables within regulatory participation. At the embedding stage, termination and reintegration are treated as elements of coupling relations. Withdrawal modifies the configuration of constraints and affordances within the socio-technological ecology, contributing to its ongoing reorganization. At the evaluative stage, dismantling events are not interpreted merely as failures but as diagnostic moments. They reveal tensions within patterns of co-regulation and provide insight into how artificial systems contribute to, or destabilize, systemic viability across time.

Through this articulation, techno-apoptosis serves as a operative principle within the Gaian framework. It renders lifecycle transitions experimentally tractable in third-order ecologies, while leaving open the possibility of alternative operative principles capable of addressing other dimensions of extended regulation.

Table 4. *Techno-apoptosis as a Gaian modelling principle*

Dimension	*Classical Synthetic Focus*	*Gaian Synthetic Focus*	*Techno-Apoptotic Modulation*
Target of modelling	Generation and control of target dynamics within bounded modelling ecologies	Regulatory contribution	Lifecycle limits as regulatory variable
Embedding	Task-oriented	Co-regulatory ecological embedding	Withdrawal modifies coupling relations
Evaluation	Comparative adequacy of generated dynamics within the modelling ecology	Systemic viability across coupling trajectories	Termination as diagnostic moment

7. Synthetic Modelling as Co-Regulatory Inquiry

7.1 Modelling Co-Regulatory Contribution Synthetically

The Gaian reorientation of the synthetic approach reframes the epistemic target of the interactionist commitments that have shaped synthetic modelling since embodied AI and artificial life. In classical synthetic practice, behaviour generation designates the capacity of a constructed system to produce relevant dynamics through engineered couplings among the system's organization, material embodiment, and a bounded environment. Under Gaian constraints, the question is no longer only whether such dynamics can be generated, but what kind of regulatory contribution they instantiate once the artefact is treated as an integrated component in extended configurations of regulation.

This shift is best understood as a change of modelling scale and of what counts as a modelling-relevant hypothesis. In *Sections 4* and *5* we argued that synthetic interactionism has historically operated within locally engineered ecologies whose boundaries, interfaces, and resources are curated to render dynamics tractable. When synthetic systems migrate beyond these bounded ecologies — particularly in robotics — the regime of coupling changes qualitatively. The system's operation becomes entangled with maintenance infrastructures, material flows, institutional practices, energy regimes, and temporal trajectories that exceed the experimental frame. Under these conditions, modelling cannot remain focused on locally generated behaviour alone. It must also address how regulatory contribution is sustained, transformed, and discontinued over time within extended couplings.

Crucially, this reframing does not abandon the heuristic of the possible, but extends it (*Section 4.1*). Synthetic pluralism no longer concerns only alternative mechanisms capable of generating analogous behaviours, but also alternative configurations of coupling through which regulatory coherence can be maintained, modified, or re-established across time. What is explored is not simply how a system behaves, but how a system's organization, interfaces, and lifecycle transitions contribute to, or destabilize, patterns of regulation in which other heterogeneous components — human, artificial, infrastructural, ecological — also participate.

This is why the Gaian turn should not be confused with biomimetic replication. The modelling target is not to copy natural regulation as such, but to articulate experimentally tractable principles of co-regulation that cut across system, subsystems, and environment and can be constructed, embedded, and compared within the Gaian synthetic cycle (*Section 5.4*). In this expanded space, it becomes legitimate — and epistemically productive — to test regulatory principles in synthetic configurations that do not belong to the original biological domain, provided the modelling claim is explicit. The aim is to explore the conditions under which a constructed configuration can instantiate viable regulatory participation under Earth-system constraints.

Techno-apoptosis, as developed in *Section 6*, exemplifies this point. It functions as one modelling operator that renders lifecycle limits — termination, dismantling, reintegration — experimentally accessible as a dimension of regulatory contribution. Other operators may target different variables of extended regulation (e.g., maintainability, infrastructural dependence, repair ecologies, distributed governance of withdrawal). What unifies these operators is an epistemological shift: once co-regulatory contribution becomes a modelling target, synthetic inquiry must articulate the temporal, material, and infrastructural conditions through which regulatory coherence is enacted and reconfigured across scale.

In sum, the Gaian reorientation reframes behaviour generation within a broader modelling problem: the viability of regulatory configurations over time. This reframing is what makes sustainability epistemically central, rather than an external design concern.

7.2 Sustainability as a Property of Regulatory Configurations

Once synthetic modelling is reformulated in co-regulatory terms, sustainability can no longer be treated as an intrinsic attribute of individual artefacts, nor can it be reduced to device-level efficiency, material optimization, or end-of-life management conceived as a downstream engineering requirement. These approaches remain artefact-bounded. They evaluate properties of discrete units while leaving largely implicit the extended couplings — maintenance infrastructures, reuse pathways, institutional practices, material and energetic dependencies — through which artefacts persist, operate, and transform.

Within a Gaian synthetic perspective, sustainability becomes visible as a property of regulatory configurations. What is sustained is not the artefact as such, but the coherence, transformability, and renewability of patterns of coordinated interaction among heterogeneous components: artefacts, users, repair and maintenance practices, supply chains, standards, infrastructures, waste and reuse ecologies, and the material flows that connect them. In this sense, sustainability is inseparable from questions of participation: how an artificial system is integrated, how it is maintained and repaired, how it is reconfigured or withdrawn, and how these transitions reorganize the regulatory field in which the system is embedded.

This systemic view aligns with recent epistemological analyses showing that in socio-techno-ecological configurations viability often depends on distributed practices of coordination and renewal rather than on the internal design of a device alone (Blinded; Blinded). In such contexts, a robot's discontinuation is not merely the endpoint of a product lifecycle, but a reconfiguration event that redistributes constraints, resources, and dependencies. Under Gaian constraints, these events become epistemically relevant and must be modelled as part of the regulatory dynamics at stake — not treated as externalities.

From a third-order cybernetic standpoint, the implication is that regulation cannot be localized within a single system–observer unit. It unfolds within self-developing socio-techno-ecological environments shaped by the activity of multiple agents and by historically evolving infrastructures. The Gaian turn deepens this insight by treating Earth-system coupling as the horizon that makes boundedness, multi-scale dependency, and temporal viability unavoidable. Consequently, synthetic modelling oriented toward co-regulation must render explicit the boundaries, constraints, and coupling relations that classical synthetic practice could leave implicit in bounded experimental ecologies.

On this basis, sustainability is an epistemological condition. It names what becomes relevant to model once artificial systems are treated as integrated components in extended configurations of regulation under bounded constraints. This is why the Gaian turn does not add sustainability "on top of" the synthetic approach, but re-specifies the object of synthetic inquiry: not relatively self-contained artefacts, but the viability of regulatory configurations in which artefacts participate — across time, scale, and material limitation.

This re-specification entails epistemological consequences: it expands what counts as a modelling-relevant hypothesis, shifts evaluation from local performance to systemic contribution across lifecycle trajectories, and foregrounds the reflexive role of modelling practices within the configurations they investigate."

8. Methodological Engagements within a Gaian Reorientation

The Gaian reorientation establishes methodological conditions for engaging extended regulation without abandoning the experimental logic of understanding by building. Rather than prescribing specific design solutions, it reformulates what synthetic modelling is required to make explicit and render experimentally tractable once artificial systems are recognised as integrated components in extended configurations of regulation under Earth-system constraints. In this setting, interactionism is scaled up. Modelling targets not only the generation of locally observable dynamics within bounded experimental ecologies, but the conditions under which co-regulatory participation can be sustained, transformed, and discontinued across time within extended couplings.

To articulate this shift in methodological terms, we summarize five Gaian commitments (M1–M5), which specify what synthetic inquiry must render intelligible when the object of modelling is the viability of regulatory configurations.

M1. Temporal articulation of modelling objects. Synthetic inquiry has always addressed temporal dynamics (e.g., development, adaptation, learning) within constructed experimental ecologies. A Gaian reorientation shifts the epistemic status of temporality. Temporal articulation becomes a constitutive dimension of what is modelled, not only of how system dynamics unfold within a bounded setting. Operation, degradation, maintenance, reconfiguration, and withdrawal are treated as phases of regulatory contribution rather than as downstream management issues external to modelling.

M2. Explicit specification of coupling relations. Synthetic systems have always been situated; a Gaian perspective makes this situatedness methodologically explicit by requiring that relevant coupling relations be articulated as part of the modelling configuration. Material, energetic, infrastructural, and institutional relations are treated as constitutive constraints of the modelling configuration through which co-regulatory contribution becomes possible, rather than as background conditions of experimentation.

M3. Comparative inquiry across coupling trajectories. Comparison remains central to synthetic epistemology. Similarities and mismatches between natural and artificial dynamics guide iterative refinement. A Gaian reorientation broadens comparison from immediate behavioural or functional dynamics within engineered ecologies to co-regulatory trajectories across time, including divergences in coupling stability, infrastructural dependence, maintainability, and systemic reconfiguration triggered by failure or withdrawal.

M4. Modelling operators and the tractability of regulation. The Gaian reorientation is epistemological before it is technological. It requires co-regulatory participation to become experimentally tractable within synthetic inquiry. This is achieved through modelling operators, understood as principled constructs that render selected dimensions of regulation accessible to construction, embedding, and comparison, such as techno-apoptosis for lifecycle limits.

M5. Iterability under constraint. Synthetic epistemology is defined by iterative cycles of construction, embedding, and evaluation. A Gaian reorientation preserves this structure while expanding the domain of revision to include modelling assumptions about coupling relations, temporal trajectories, and boundary conditions, so that evidence emerging from degradation, maintenance, transformation, or withdrawal becomes modelling-relevant in its own right.

Table 5. *Methodological engagements within the Gaian synthetic approach.*

Proposed Engagements	***Points to be addressed***	***Examples in Electromechanical Robotics***	***Examples in Chemical Robotics***
M1 – Temporal articulation	Lifecycle phases as modelling variables	Service robot modelled with degradation thresholds and programmed modular withdrawal	Protocell with defined activation window and programmed dissolution, co-modelling function and breakdown
M2 – Explicit coupling relations	Material, energetic, infrastructural, institutional dependencies as constraints	Identical task robots under different repair infrastructures (open modular vs proprietary)	Embedding protocols specifying pH, temperature, metabolite uptake as coupling parameters
M3 – Comparative inquiry across coupling trajectories	Divergences in regulatory contribution, not only task output	Robots with equal task success but different maintenance loads and end-of-life logistics	Remediation protocells with equal neutralization but different by-products and ecological reintegration
M4 – Modelling operators for tractability	Regulatory variables made experimentally accessible	Techno-apoptotic operator for condition-based disassembly and redistribution	Programmed dissolution varying degradation kinetics and by-product composition
M5 – Iterability under constraint	Revision of boundary assumptions and coupling configurations	Iterative redesign prompted by withdrawal logistics, revising modular interfaces and embedding	Iterative reformulation of dissolution parameters after medium perturbations

These methodological commitments (M1–M5) clarify how sustainability becomes epistemically intelligible once synthetic modelling targets the viability of regulatory configurations rather than the performance of systems within circumscribed modelling ecologies. The Gaian reorientation thus proposes methodological conditions for engaging extended regulation without abandoning the experimental logic of *understanding by building*.

9. Conclusion and Future Research Directions

The Gaian turn proposed in this paper shifts the epistemological target of synthetic modelling from locally bounded artefacts to extended configurations of regulation. Under this reorientation, *understanding by building* is no longer limited to the generation of local behavioural dynamics, but must account for how artificial systems participate in, sustain, transform, and exit regulatory couplings across time under Earth-system constraints.

This reorientation does not replace the classical logic of *understanding by building*, but deepens it. The construction–embedding–comparison cycle remains central, but the domain of comparison is broadened. Divergences may emerge not only at the level of immediate function, but also at the level of coupling stability, lifecycle trajectories, infrastructural dependence, and systemic reconfiguration triggered by maintenance, failure, or withdrawal. In this sense, the Gaian perspective preserves the experimental character of synthetic epistemology while extending the scope of what can be rendered intelligible through construction.

Techno-apoptosis was introduced as one modelling operator within this expanded space. Its role is not to define the Gaian turn, but to exemplify how specific variables of extended regulation — here, lifecycle limits through termination, dismantling, and reintegration — can be made experimentally tractable. The broader claim is epistemological. Once co-regulatory contribution becomes a modelling target, synthetic inquiry must articulate the temporal, material, infrastructural, and institutional conditions that sustain or destabilize such contribution. Sustainability, in this framework, is not a property of isolated artefacts, but a question concerning the viability of regulatory configurations across time and scale.

Future research can develop this programme in at least three complementary directions. First, the Gaian reorientation calls for the systematic development of further modelling operators beyond techno-apoptosis, targeting variables such as maintainability and repair ecologies, infrastructural and energetic dependence, and the distributed governance of withdrawal within hybrid socio-techno-ecological environments. Second, it motivates comparative protocols capable of registering co-regulatory trajectories across time — how systems enter, stabilize, perturb, and exit regulatory configurations — rather than restricting comparison to task-bounded performance. Third, it requires methodological work on boundary and scale specification in synthetic ecologies, clarifying which couplings are taken as modelling-relevant and how multi-scale constraints are experimentally staged under Earth-system conditions.

Further research can be articulated from perspectives grounded in autopoietic and enactive approaches to life and cognition, in which extended processes of regulation may be interpreted as distributed cognitive dynamics (e.g., Varela, 1976; Thompson & Varela, 2001; Blinded; Rubin et al., 2021). If cognition is enacted through coordinated self-regulation across system–environment couplings, then modelling co-regulatory contribution reshapes how the boundaries and scale of cognitive systems are specified in synthetic inquiry. Under Gaian constraints, cognition cannot be modelled independently of the viability conditions of the regulatory configurations in which it unfolds. This line of inquiry opens the possibility of developing a third-order cybernetic account of sustainability as intrinsic to the modelling of cognitive organization.

This perspective resonates with the pioneering cybernetic work of Warren McCulloch, whose experimental epistemology articulated an early distributed conception of cognitive organization. In a suggestive passage, McCulloch described cognitive machines not as isolated mechanisms, but as “anastomotic” organizations — like the mouth of a river, where waters from multiple contributory streams are intertwined before reaching the sea (McCulloch, 1962; Blinded). His image is not merely rhetorical. It expresses a conception of natural and artificial systems as sites of distributed convergence, in which heterogeneous processes become mutually constraining and co-determining. In this light, the Gaian reorientation of the synthetic approach does not impose an external ethical demand upon artificial construction. Rather, it extends an anastomotic intuition already present in early cybernetic thought: machines understood not as self-contained units of control, but as participants within evolving hybrid ecologies of regulation.

In this sense, the Gaian turn, far from concluding the evolution of the synthetic approach, opens an epistemological space in which synthetic modelling remains experimental, iterative, and reflexive, while engaging more explicitly with the regulatory conditions that shape the viability of the hybrid systems in which artificial artefacts are integrated.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the authors used AI-assisted tools for language editing and clarity. The authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

No data were generated or analysed in this study.

Highlights

- Reframes synthetic modelling under systemic constraints
- Treats sustainability as an epistemic modelling condition
- Extends evaluation from task performance to systemic viability
- Introduces techno-apoptosis to model designed lifecycle limits
- Connects robotics, cybernetics, and Earth-system theory

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: