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A Blockchain-Driven Cyber-Systemic Approach to Hybrid Reality

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Abstract: Hybrid Reality (HyR) is the place where human beings and artificial entities interact. HyR modelling relies simultaneously on the cognitive power of humans and artificial entities. In addition, HyR is an evolving paradigm where natural and artificial intelligence can intervene in processes that demand proper control. This work aims to lay the foundation for a systematic approach to understanding and modeling present and future human–machine symbiosis under a systems engineering perspective. It introduces a novel cyber-systemic methodology for managing the engineering of purposeful regulation for HyR phenomena by integrating the Blockchain technology framework and principled methods of cybernetics. This formalized interdisciplinary methodology integrates system dynamics, agent-based computation, artificial intelligence, and Blockchain-powered security and safety layers. The Blockchain framework, seen under a new cyber-systemic perspective, provides new opportunities and tools for the organization and control of HyR. A Cybersystemic Security Kit is here defined as a major component of the methodology, representing a candidate to offer viable breakthroughs in the field with respect to the best practices of Industry 5.0 when a systemically augmented perspective is adopted. Ongoing research and experimentation in the real field of sustainable supply chains is used as a motivating use case to support the proposed position. The industrial target is the primary one in its multi-dimensional and multi-faceted sustainability impacts, but this study will also reveal other potential societal areas of intervention.

Keywords: blockchain; system dynamics; supply chain; design for the unexpected; systems engineering; hybrid reality

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1. Introduction

The relationship between humans and machines has always had a significant social impact, particularly since the onset of the First Industrial Revolution. Today, we are witnessing an exponential acceleration in the impact of technology on social sustainability and social responsibility in many ways. The article of Perko [1], with the use of system dynamics (SD), evidences how pathological and uncontrollable dynamics occur in the context of HyR (Hybrid Reality) concerning, among others, the following: transparency and accountability—owing to data asymmetry; respect for stakeholders and ethical behaviour; respect for the rule of law; respect for international norms of behaviour; respect for human rights, in particular concerning digital identities; and social responsibility in HyR. With that study, a gap was acknowledged regarding the need for an interdisciplinary, comprehensive,

and practical framework involving at the same time technologists, scientists, regulator entities, politics, and possibly many other societal stakeholders that are interested in HyR.

The pathological patterns of HyR are exacerbated by the current, and continuously increasing, hype around AI (artificial intelligence) and its unexpected, unexplainable, and unknown possibilities. Many authors have a pessimistic view about the control of HyR. For example, in [2], the author argues that the hope of keeping a human-equivalent artificial agent under control is illusory. Following or contrasting this kind of foresight is out of the scope of our present work. However, the current state of HyR presents many challenges in practical situations that would benefit a stable interdisciplinary program designed for achieving sustainable control of HyR phenomena.

1.1. HyR Definition, Examples, and Issues

We start with the definition of Hybrid Reality (HyR) given by Perko [1]. According to his definition, HyR is the place where human beings and artificial entities interact; it is constructed, controlled, and modeled by both agencies. HyR is there also defined as an ongoing process in which artificial intelligence (AI) technology is gradually introduced as an active stakeholder in the construction of reality. In addition, it is said to represent a brief, dynamic, unstable period in which people and AI technology coexist and affect each other, with technology not merely modifying human existence but also being shaped by human interactions. This multifaceted definition aims to embrace at once several aspects that proceed in multiple dimensions, from the physical to the behavioural and then the organizational.

For the purposes of this study, it is necessary to both extend and refine this definition. The most appropriate term that, in our view, effectively captures and encompasses both the aspects highlighted by Perko and those that will be addressed in the present work is the concept of HyR, which we propose to define as a phenomenon. A phenomenon is any observable event, fact, or occurrence that can be perceived or experienced, whether it is physical, social, psychological, or conceptual. Defining HyR as a phenomenon suggests that it is being regarded as a distinct and observable event or pattern that merits analysis and interpretation.

The domain of HyR is not merely a digital augmentation of the physical world but a dynamically evolving reality construction where human cognition, artificial intelligence, and cyber-physical systems converge to shape new paradigms of interaction, decision-making, and systemic control. As societies and industries become increasingly intertwined with this form of existence, the understanding, modeling, and regulation of these interactions become critical to ensuring stability, adaptability, and sustainability.

Although HyR might resonate with the digital twin concept, the two have to be clearly distinguished. A digital twin is a virtual representation of a physical object, process, or system that serves as its real-time digital counterpart. This model is continuously updated with data from its physical counterpart, allowing for monitoring, analysis, and simulation of real-world conditions. As such, a digital twin is part of the HyR phenomenon. However, the HyR phenomenon does not only consider digital artificial technologies, but all kind of artifacts (and so technologies) and their interaction and encounter with nature and natural beings.

In pragmatic terms, the motivation underpinning this work was elicited by the previous work carried out in [1] when coupling it with a highly realistic and impactful case study on sustainable food supply chains [3]. This case study will serve as both an initial prototype and a preparatory framework for the future empirical validation of the efficacy and utility of the HyR vision and its associated model. In the course of this research project, the HyR phenomenon has clearly manifested, thereby inspiring the methodological approach

presented herein. Typical challenges to the sustainability of HyR, in the food supply chain case, are as follows:

- Human actors, workers, and organizations do not always accept being controlled by sensors and monitors;
- In particular, small and medium enterprises have to overcome many cost, technological, and procedural barriers to deal with increased digitization and sustainability requirements from regulations and laws;
- Some of the information has to remain hidden between the participants in the supply chain, although continuous improvements require technological upgrades and global optimizations across all the participants;
- A chain of trust has to be created in order to address the Farm-to-Fork sustainability, which involves automation, technologies, and humans at the same time.

1.2. Research Question and Proposed Approach

As of the time of writing, the current state of the art in intelligent artifacts has not yet exhibited the capability for machines to autonomously generate sophisticated models of the dynamic processes necessary for regulating or influencing the HyR system [4]. It is still up to humans to prepare and shape the terrain of this new reality, through coordinated and joint (transdisciplinary) action in the areas of cybernetics, systems engineering, and systems thinking. Human expertise remains pivotal in guiding the evolution of these systems towards greater resilience, sustainability, and ethical governance.

The purposeful control of causal relationships in HyR demands a renewed systems perspective on the interactions between humans and their artifacts. Artifacts today are such complex systems that are possibly destined to co-create a reality and a symbiosis in which the natural and machines co-evolve and survive in some form of sustainable equilibrium [5]. In addition, systemic interpretation of HyR requires a new epistemology in which objects of reality have dual and simultaneous relations. On one hand, relations involve humans and their behaviour as belonging to a physical reality that machines can sense and act upon. On the other hand, humans rely on artifacts to extend their range of actions from a purely physical environment to a virtual or digitally twinned environment, using machines as epistemic structures [6,7]. These two competing relations within HyR together constitute a relational circuit. This circuit takes on the significance of regulation and control when placed within the framework of cybernetics. The two relations create a circular causal loop and so, by definition, a cybernetics of HyR.

Thus, it is now imperative to tackle the multi-faceted challenges emerging across diverse sectors—including industrial and economic production domains—using groundbreaking approaches for developing a comprehensive model of constantly evolving HyR. In this work, we propose some possibly useful steps towards this goal.

The research question that this work will answer is as follows:

Is it possible to establish a comprehensive cyber-systemic methodology that makes HyR a controllable and sustainable phenomenon?

We will follow a pragmatic constructivistic approach to the HyR phenomenon. A constructivist perspective began to gain scientific and technological relevance long ago, at least since N. Wiener's early work on purposeful causal relations between machines and natural agents [8], and then cybernetics. Building on the foundations of cybernetics, we can extend and generalize the phenomenon of HyR beyond the definition of AI, in constant never-ending motion, to embrace both the past and future of the intelligence expressed by artifacts, beyond related (hard) philosophical questions. The HyR transformation depends on interactions between natural and artificial agencies operating concurrently. Addressing this complexity requires a cyber-systemic approach, integrating principles from cybernetics

and SD to enable robust modeling and control. This work adopts Ashby's Law of Requisite Variety as a guiding principle, ensuring that regulatory mechanisms within HyR possess sufficient adaptability to match the system's intrinsic variability.

1.3. Nature and Plan of the Study

This manuscript is inherently positional, offering a comprehensive new methodology as its primary contribution. It is not intended to present experimental data or empirical validation; rather, it aims to establish a conceptual foundation for future research endeavours. The proposed methodology will define the underlying philosophy, principles, and rationale guiding the selection and application of specific methods. Some of these methods will be applied from a new perspective, but their factual implementation and demonstration require a broader activity framework, which is beyond the scope of this work. The overarching methodology will illuminate and steer each engineering step within these methods, providing a coherent direction toward a purposeful and integrated whole.

This study lays the foundation for an empirical validation framework, extending beyond theory to address real-world applications. Its implications span both industrial systems and broader societal contexts, where human–artificial symbiosis is increasingly pervasive. The proposed methodology aims to support the ethical, efficient, and resilient evolution of HyR, grounded in cybernetics and systems thinking, and made operational through rigorous systems engineering practices to ensure repeatability, analyzability, and transferability.

The proposed methodology incorporates Blockchain (BC) as a foundational infrastructure to support the sustainability of engineering within HyR. Sustainability is here understood in the comprehensive sense of the United Nations Sustainable Development Goals (SDGs) [9]. BC here extends beyond its conventional domains (e.g., finance and security), functioning as a trust-enabling infrastructure for verifiable, immutable interactions between human and artificial agents—both when humans act on machines and when machines act upon or through humans. By integrating BC with systemic methodologies, this study aims to establish a cyber-systemic security framework that maintains sustainability equilibrium in HyR environments. As explored in the presented analysis, BC technologies offer concrete opportunities for addressing trust-related challenges. In collective processes, both human and machine participants must be trustworthy, and all intermediaries in data transmission must be verifiable. This necessity underpins key open problems such as Verifiable Computation [10] and the Oracle Problem [11–21], which are particularly relevant in the HyR context.

The main expected outcome of this work is a methodology that will be developed in three major steps:

1. The first step is a thorough operational definition of an HyR model that crisply situates the area of intervention of the HyR (Section 3.1) and related formal tools to enable algorithmic processes in HyR (Section 3.2).
2. The second step is the positioning of the HyR problem under the perspective of Ross Ashby's Law of Requisite Variety and cybernetics (Section 3.3).
3. The final step is to use the former methods to define a systematic workflow (Section 4.1), which is a container that integrates the methodological components based on SD (Section 4.2), the design of HyR regulators (Section 4.3), and the introduction of the BC framework possibilities (Section 4.4). As shown in the following, SD methods will place a decisive role in BC-related technologies when it comes to the dynamics of control in the HyR problem by means of tailored systems engineering processes.

In Section 2, the motivating background and literature are reported. In Section 3, a set of methods are proposed as an essential toolbox to achieve consistent modeling of HyR and components for the construction of the methodology here proposed. In Section 4, a methodology is the result of the appropriate use of the methods formerly introduced, together with further methods already available in the context of systems engineering and technologies in the BC framework. A step-by-step explanation of the methodology against a selected use case is made in Section 5. A final discussion is made in Section 6 with respect to related work. Conclusions are drawn in Section 7.

2. Background, Context, and Motivation

In this section, we provide an introductory literature review that prepares the ground for the subsequent core of the article. The several subsections that follow will be further reinforced and expanded in Section 6 for a final discussion of related work.

2.1. Challenges in Human–Machine Interaction

Recognizing AI as an active stakeholder is crucial for understanding HyR. AI technologies co-create environments and experiences through data gathering, analysis, and decision-making. Perko's work emphasizes reciprocity in human–AI exchanges [1], laying the foundation for a framework that addresses sustainability challenges in HyR through interdisciplinary collaboration.

To present the key challenges, we summarize them in Table 1.

Table 1. Challenges in human–machine interaction.

Challenge	Description and Reference(s)
AI as a stakeholder	Co-creation of experiences in HyR requires recognition of AI's active role in human–AI reciprocity [1,5].
Ethical decision-making and stakeholder engagement	Organizations must consider ethical implications of AI involvement in decisions, especially in supply chains [22]. Multidisciplinary engagement is crucial for fostering innovation with transdisciplinary skills in cybersecurity [23]. Proactive strategies are needed to address AI's societal and environmental consequences [24].
Human-centered and value sensitive design	Emphasizing joint cognitive systems and user motivations helps align Industry 5.0 teams with sustainability goals [25]. Integration of sustainable values into HMI design improves user experience and satisfaction [26].
Shared control systems	Intelligent, context-aware systems support hybrid capabilities between humans and machines [27,28].
Systems engineering and AI integration	Difficulties remain in applying System Dynamics methods to LLM-based simulations [4,29,30].
Modeling complexity in HyR	While agent-based systems support autonomy and collaboration, they are not yet sufficient for complex modeling and control as required by HyR [31–35].

This table summarizes a few but representative challenges and research directions, highlighting the interdisciplinary nature and technical complexity of sustainable human–machine interaction.

2.2. Cybernetics in Sustainable Systems Design

In [36], the author explores how systems regulate, adapt, evolve, and self-organize, focusing on the structures and mechanisms driving their dynamics. Sustainability is defined in the paper as a dynamic equilibrium where a population realizes its potential without causing irreversible environmental harm. However, the study lacks a methodology for explicitly designing a controller system, which this work aims to address.

While the authors of [37] find an underlying paradigm for possible indicators of sustainability, possibly enabling Lyapunov-based control techniques (see, for example, [6]), they acknowledge that the question remains how to effectively embed and embody those schemes in networks of artificial systems, humans or their extensions. This is indeed one of the major goals of the methodology achieved here.

In [38], cybernetics is used to express a holistic and unifying approach to the micro, meso, and macro levels of social responsibility, though without any SD argument. In [39], higher-order cybernetics is summoned to enhance the effectiveness of cybernetic analysis. However, to date, the role of higher-third-order cybernetics is difficult to apply and master [40], especially for what it would entail in practical terms in today's systems engineering. But the work carried out here should create an initial foundation for reuniting practice with analysis.

Today's highly distributed and heterogeneous systems pose growing challenges for traditional cybernetics [41]. However, this work highlights that sustainable human–artificial interaction is possible through cybernetics and enabling technologies like the BC framework, if supported by systemic systems engineering. In [42], the author supports the idea that the technical tools today available to systems engineering and cybernetics can provide solidity and tractability to sustainability sciences.

2.3. Holonic Agents in HyR

The agents (actors) in many cyber-physical processes like HyR processes have to bear two faces: one directed inward to their own locally controlled processes, and one outward directed to the purposeful organization of a collective whole. One notable example is the supply chain. This concept is known as the *Janus effect* of holonic entities, initially used in [43]. By means of the holonic concept, the point of contact between two worlds can be handled with a suitable entity. Complexity can be tamed when a recursive structure of simplification breaks down the otherwise irreducible diaphragm between the whole and the parts, particularly when these come from two completely separate realities such as the natural and the machine [6,7]. The holonic paradigm provides a function of filtering in one direction and of amplifying in the other [43]. The holonic paradigm allows a direct mapping between holons and Ross Ashby's concept of variety amplification and attenuation [44]. A recent account of the relationship between the holonic concept and the cybernetics of problems in the industrial context is provided in [45].

Holarchies and holons were first applied in engineering within the manufacturing sector. Holonic Control Architectures (HCAs), composed of purpose-driven holons organized into self-similar holarchies, have become a promising control paradigm over the past two decades [46,47]. The holonic paradigm goes along with a rather long-standing search for systems that can handle uncertainty and that have capabilities of self-organizing. Among many important studies, one of those best-known studies in the industrial context is the work of [48], who coined the Design for the Unexpected (D4U) design pattern, where the holonic and multi-agent paradigm is kept as central.

With the introduction of holons, any hierarchy can become a holarchy that features holons as constituent nodes. Holarchies constitute structures that can be overlaid on a cyber-physical system of systems that acts as a system of systems controller. For a

comprehensive review of holonic paradigms and the relevant literature, refer to [45] and the references therein.

2.4. A Role for Blockchain Technologies in Industrial HyR Cases

The BC is increasingly being explored as a mediator between humans and AI. Though still in its early stages, studies suggest BC can ensure transaction integrity via smart contracts [49] and enhance privacy through decentralized data management, enabling user control with SSI (self-sovereign identity) and ZKPs (zero-knowledge proofs) [50,51].

Academic research on the blockchain emphasizes traceability, transparency, and quality assurance, while industry focuses on data provenance, trust, and authenticity as key values [52]. This reveals a requirement for new systemic terrain where better interdisciplinary alignment could help unlock the full potential of the BC framework.

The authors of [10] emphasize BC as a trust-enabling layer in supply chains, facilitating secure human–AI interactions through immutable data exchange. Integrating BC with ZKPs supports privacy and traceability. The Smart Data System (SDS) architecture (see also Section 5.1) combines decentralized control with collaborative process management, enabling structured human–AI collaboration. The limits and challenges are on current capabilities and scalability of BC technologies.

The review given in [53] shows that BC can enhance supply chain transparency and efficiency through a secure, tamper-proof transaction ledger. However, its adoption remains in early stages, with many organizations still assessing its impact.

In Industry 5.0, integrating blockchain with IoT and AI offers benefits like improved security and real-time collaboration [54], but faces challenges such as scalability, privacy, and computational cost. A more pragmatic approach, such as SD (Section 4.2), may provide key solutions.

Despite its potential, BC faces challenges such as risk, scalability, compliance, and governance. In construction, studies highlight benefits like transparency and fewer disputes [55], but also note integration issues and stakeholder resistance [56]. BPMN choreographies have been proposed to mitigate these barriers by means of BC [57,58].

As noted in [59], understanding BC's role in supply chains is essential for effective strategy, especially in building trust—though the role of artificial stakeholders remains underexplored. In agri-food supply chains, BC improves traceability, transparency, and data integrity [60–66], but challenges like privacy, scalability, and integration persist. Addressing these demands robust governance, industry alignment, and a systemic framework.

Integrating blockchain into supply chains, such as in Operator 5.0 systems [67], enhances efficiency, transparency, and human–machine collaboration. Smart agent systems for federated learning improve secure data sharing and incentivize quality contributions [68]. Cross-chain interoperability with oracles [16] and BC architectural patterns [69] support scalable, effective human–machine interaction. A bibliometric review [70] shows the promise of BC and machine learning integration for security and privacy, especially in healthcare and finance.

2.5. Purpose and Relevance

The findings presented in this literature review support the view that top–down, brute-force, and strictly disciplinary approaches alone are insufficient to address the complexity of the challenges posed by HyR. The ongoing wave of pervasive digital transformation is likely to encounter saturation effects and diminishing returns, particularly when societal and technological issues must be addressed simultaneously. Moreover, even the promising advancements in AI and BC technologies have yet to converge toward a sustainable point of focus and equilibrium.

A more systemic and holistic vision of these problems must be supported that also takes into account the bottom–up perspective and peculiarities of the actors participating in collective and societal processes.

Given the limitations of currently available technologies, the methodology proposed in this study incorporates the constraints imposed by Best Available Technologies (BATs) as a foundation for an integrated design and decision-making process related to the engineering and deployment of sustainable solutions in the context of HyR.

Overall, the analyses or technical results referenced herein do not converge into a coherent approach with general validity. Therefore, in this paper, we are looking for a methodology that brings together soft and hard science challenges for HyR in a holistic interdisciplinary framework that integrates cybernetics, systems engineering, systems theory, AI, and BC.

How, why, and in which way all the above concepts, entities, and technologies have to be harmonized and used for a new direction in the purposeful control of HyR represent the focus of the rest of this paper.

3. Methods

In this section, definitions and techniques are introduced that will be used as the ground for the development of the HyR control methodology. In the following sections, some formal tools are devised to strengthen the methodological approach. At the same time, these tools are designed to be reusable and extendable in various ways, including for future, scientific, incremental, and experimental work.

With the formal frame here achieved, "hard" engineering and scientific techniques can be applied to a matter that usually is attacked by softer scientific methodologies. With the definition of some formal tools, we will be able to set up a working framework on processes that to a large extent can be measured, reused, and compounded, as needed in any engineering project.

This constitutes a clear link to the main definition of cybernetics, where "everything is a system". Systems are prone to be modeled and controllable as any purposeful machine. For a discussion on this cybernetics perspective with historical details, we refer the reader to [45] and the references therein.

Therefore, Section 3.1 starts with providing the fundamental definition and bricks of the HyR problem. This will establish a first rigorous layer for subsequent incremental constructions. On this ground, Section 3.2 will provide hooks to state machines and automata theory. It will allow the methodology to be replicable and algorithmic in some respects. Finally, Section 3.3 will provide a set of definitions that will create the link between the automation and logic of the HyR process to a problem in typical cybernetics form.

3.1. Operational Definition of Scope of Hybrid Reality

It is important to understand, first of all, when it can be said that a problem involves HyR. This definition is important because it is the first step towards a general model of the HyR problem and systemically framed as an irreducible whole of interactions between elements of reality and agents.

To define with some consistency and rigour the scope of the HyR modelling, a set of positions have to be made. First, the definition of the two principal entities of the HyR problem: agency and the environment in which it is implemented through agents of a general type, natural or artificial.

3.1.1. Definition of Agency and Environment

Agency refers to the capacity of an agent to act autonomously in order to pursue goals. An agent is typically defined as an entity that perceives its environment (via sensors or inputs), decides what to do (based on rules, learning, or optimization), and acts upon the environment (via actuators or outputs). In philosophy or social science, agency also implies intentionality, but in computer science and engineering, it is more about functional autonomy.

The environment is everything external to the agent that it can perceive or influence. The environment includes other agents, physical surroundings, data (e.g., temperature, space), data structures in digital context, and natural beings. For example, in the context of Industry 5.0, a collaborative robot (cobot) in a smart factory is an agent, its agency includes its ability to adjust grip strength based on the object type, and the environment includes the workspace, nearby workers, sensors, and production tasks.

At this point, we find four possible combinations of agency and environment, as both can either belong to the sphere of the natural or the artificial.

3.1.2. The Agency–Environment Matrix

In Figure 1, a matrix is shown to express the four possible classes of interactions between an agency and the environment that is the object of its action [71]. This is a very rough classification, albeit useful to some extent, as we shall see. Depending on the specific coupling of agency and environment types, the interaction can be a form of enaction [71–73] in a reflexive active environment [6,74] or a simpler action in general.

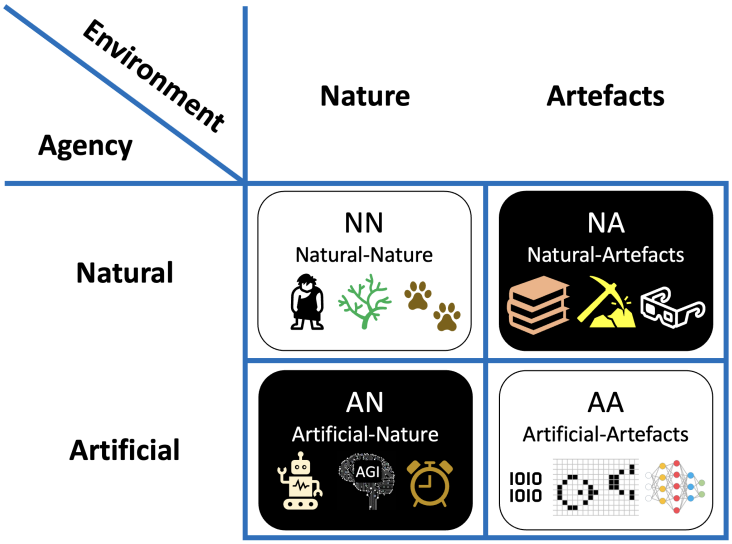


Figure 1. Scope of intervention of HyR model: Agency–Environment matrix (AE matrix). Black off-diagonal quadrants are of primary interest for HyR.

A simple action is merely executed, while enaction involves a process of embodied adaptation and co-construction of meaning. An enactive approach challenges the idea of cognition as mere computation, emphasizing how knowledge and perception emerge through interaction and lived experience.

A clarifying example is a simple action made by a human like pressing a button to turn on a light. A person sees a button, decides to press it, and the light turns on. The action follows a stimulus–response model. The agent perceives the button, executes a movement, and achieves an expected outcome. The world is treated as pre-given; the agent does not actively reshape their perception of it but merely responds. And this is the classic cognitivist view of action.

At the same time, some actions can be modeled by a more complex process and are not always easily decomposable. These are enactions—for example, learning to ride a bicycle. Instead of just executing a movement (e.g., pedaling), the cyclist gradually develops a dynamic sensorimotor coordination with the environment. Balance emerges through interaction: the person perceives and adapts in real time, feeling how their body, gravity, and the bicycle interact. The ability to ride is not encoded in pre-defined rules but emerges from embodied exploration and sensorimotor feedback loops. The experience transforms the individual. Once learned, balancing on a bike becomes an intrinsic skill integrated into their perceptual–motor repertoire.

Nonetheless, we stop here in delving into philosophical questions about agency and their definitions. The only level here required is the acknowledgment of some kind of interaction that involves agents and their environment, however complex the nature of the interaction.

In Figure 1, four quadrants are included to highlight the parts that fall under the scope of HyR modelling. These are the black-background quadrants in the off-diagonal of the matrix.

In the diagonal of the matrix, the *NN* (Natural–Nature) quadrant represents the interaction between a natural agency and nature with its living or non-living objects or entities. Humans, animals, and plants appear in the stylized figures of the matrix quadrant as examples of natural agencies. However, we note that such agents could become the environment of other agents in certain cases—for example, bacteria infecting a living being. These interactions can indeed be reciprocal and circular in many ways—which is in very brief a reflexive active environment [6,74].

The *AA* (Artificial–Artifacts) quadrant, on the opposite side, is the place where artificial entities interact with artificial environments. Here, the icons in Figure 1 represent agents/environments such as digital machines, cellular automata, and neural networks.

These two quadrants are so far, and historically, the best modeled ones. The first, the *NN*, is the object of naturalistic sciences and disciplines. The *AA* context is an elective and well-developed playing field for disciplines and technologies coming, for the most part today, from computer science.

Different from the *NN* and the *AA* quadrants, the other two quadrants, namely, the *NA* (Natural-Artefacts) and the *AN* (Artificial-Nature) quadrants, might still deserve a unified and coherent framework to be addressed. Both deal with the contact between the artificial and the natural, two neatly separate phenomena in ordinary reality.

The *NA* quadrant represents the natural agencies that interact with artifacts that do not belong to nature. The *AN* quadrant is the dual of *NA*, and deals with artificial entities whose design is rich enough to produce their effects on natural entities.

The icons in the *NA* quadrant in Figure 1 convey the concept that a natural agent, a human in this case, may interact with artifacts like books, tools, or extended reality means. The interaction may happen also reversed as in the *AN* quadrant, where a machine provides some effects in the natural environment. Examples include collaborative robots that influence human behavior, or an AI system that autonomously communicates strategic decisions to humans and influences them through information regarding updates or maintenance required for its infrastructure. A limit case is an alarm clock that forces a human being to wake up, probably sooner than desired.

In Table 2, a synthetic and non-exhaustive taxonomy of the environments and agencies that appear in their respective quadrants is provided. In addition, in the same table, a taxonomy is presented on the kind of interactions that might occur in each of the quadrants. These interactions have been divided into three major categories:

- *Create*—The action of creating or changing the structure and configuration of some kind of environment by the agency.
- *Learn*—All the actions that pertain to observing, sensing, perceiving, and learning that the agency performs in the interested environment, mostly to gather and process information, are collected in this category.
- *Use*—The agency at some points performs actions that exploit the structure, the substance, and the essence of the environment. This interaction is the "doing" beyond observing.

Of course, the boundaries of these categories are not at all crisp. For example, usually the interaction of an animal with an environment comprises a mix of the three aspects at once. It is well known, especially in the concept of enaction, that observation requires some "touching" and "doing" to be achieved, and maybe the creation of new epistemic structures as well [71–73].

However, this simple model is adopted to try to group actions in a way that allows for a dynamic model of the processes that make up the chain of interactions in the matrix in Figure 1. It will promote the matrix to a three-dimensional model, where the type of interaction (*Create*, *Learn*, or *Use*) constitutes the third dimension. Having gained a third dimension over the *AE matrix*, this new parallelepiped will be called the *AE space*. A rendering of this space is shown in Figure 2.

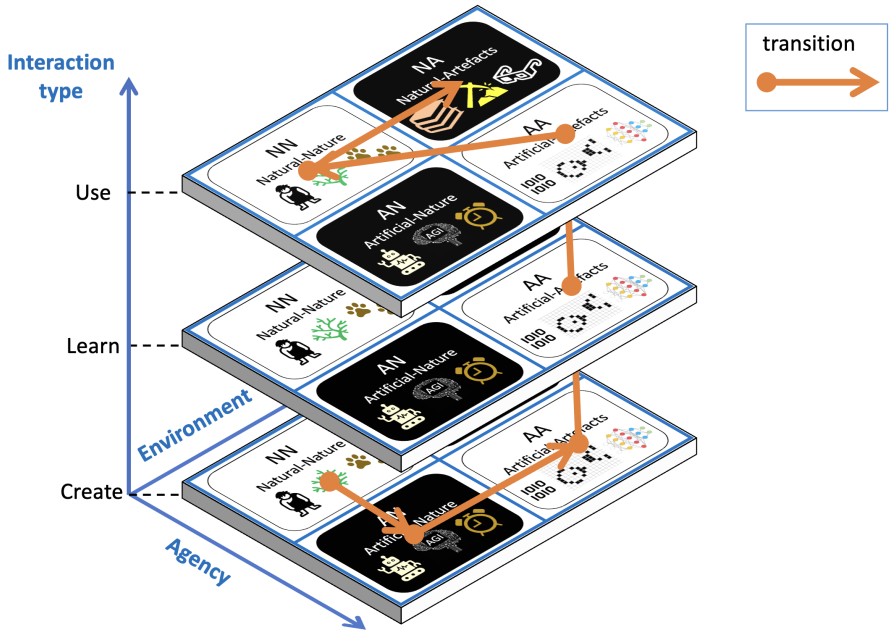


Figure 2. A pictorial rendering of the AE space. Transitions due to progressing interactions are shown. They happen in three dimensions.

In this figure, it is shown how the *AE matrix* is extended with a third dimension that is given by the interaction type. The arrows indicate the possible path of an *AE process* in this *AE space*. Any path is allowed between the 12 points of the *AE space*.

The *AE process* will start from one point of the *AE space* and will form a trajectory in that space. Any type of interaction is started at some point in time and destined to end as well. The developments of any interaction will make the *AE process* proceed step by step in the discrete *AE space*.

In order to describe the dynamics and evolution of the *AE process* in detail, the next section suggests some formal definitions to promote the *AE space* into a full-fledged state space.

Table 2. Details of the Agency–Environment matrix and model.

Agency–Environment (AE) Quadrant	Agency	Environment	Create	Learn	Use
Natural–Nature (NN)	Natural elements; natural biological structures; animals; humans	Natural elements; biological entities; animals; humans	Giving birth; allopoiesis; proliferations; natural transformations	Naturalistic sciences; observations; natural learning	Living; natural processes
Natural–Artifacts (NA)	Natural elements; natural biological structures; animals; humans	Tools; artifacts; machines; computing systems; virtual worlds	Design and production; writing documents; virtual reality creations; digital twin creation; hypothesis abduction	Observe; natural learning; understanding	Use of tools or artifacts; disruption or dissolution of artifacts
Artificial–Nature (AN)	Computational system; autonomous machine; software program; artifacts and objects; automation; mechanic system; robotic system; embodiment of AGI (artificial general intelligence)	Physical world; biological structures; animals and humans	Production of data, information, and knowledge through communication; enable or disable autopoies or allopoiesis of new biological structures	Photography; sensors; machine learning; monitoring; transduction	Energy intake by transformation of raw material; material for productions; good, bad, or purposeful effects on humans and animals; transduction; communications
Artificial–Artifacts (AA)	Computational system; autonomous machine; software program; artifacts and objects; automation; mechanic system; robotic system; AGI (artificial general intelligence)	Digital worlds; cellular automata; evolutionary algorithms; multi-agent systems; artificial life; emergence; artificial self; autonomic systems; mechanic systems; artifacts	Program creation; self-rewriting; agent offspring spawning; delegated MAS [48]; digital allopoiesis; digital genetic offsprings; production of artifacts; production of data, information, and knowledge; synthesis of artficial structures; synthesis of biological structures	Self-learning; state observers; machine learning; sensors	Program execution; communications; material for productions; good, bad, or purposeful effects on artifacts or artificial objects

3.2. Formal Tools for HyR

A process, which we call the *AE process*, is used to model and map any development of reality due to interactions between agents and environments. If a process can be broken down into distinct stages or states, each with rules for transitioning from one state to the next, a state machine can model this kind of process effectively. If we see this state machine like an automaton, a suitable representation can be used to describe and formally control this *AE process*, by means of the following definitions:

Let a state **s** of the *AE process* be defined as a triple $< a, e, i >$, where a is the type of agency $a \in A = \{Natural, Artificial\}$, e is the type of the environment $e \in E = \{Nature, Artefact\}$, and i is the type of interaction $i \in I = \{Create, Learn, Use\}$. With this triple, the *AE space* defined before can be completely described.

Transitions across the states are defined with the rules and conditions that cause the process to move from one state to another. A transition δ of this state machine and process is performed when the interaction i in the quadrant $< a, e >$ produces an event t. The event type can be related to how the agent performs in its environment. It depends on the affordances and capabilities of the agent in a specific state. Events are triggered by a condition of the current state. The set of the events is kept limited here to a set like $T = \{Completed, Progress, Interrupt, Fail, Reject\}$. The set elements can be defined as follows:

- *Completed*—The event that is triggered by the completion of an interaction in a certain state **s**. It means that the purpose of the interaction between the agent and the environment is fulfilled and it makes no sense to continue in the same state.
- *Progress*—This is the event that is triggered when the agent does not see an opportunity to continue with the same interaction because other opportunities to change the current state are found; the change to another state occurs before the interaction in that state is completed.
- *Interrupt*—The agent's interaction is interrupted by some external and unforeseen conditions. A switch of the state is needed to try other routes.
- *Fail*—The agent at some point does not find a possibility to complete the interaction in the current state and is forced to switch.
- *Reject*—In this case, the agent sees no opportunities or rewards in continuing with the interaction. A state switch is made to try to land into a better situation.

Of course, underlying this whole process is the agent's goal of creating benefits and continuous progress in the environment in which it is involved. As far as the present case is concerned, this goal has to do, as we will discuss later, with sustainability, and the actions are directed toward social good. In general, the process behind this model may also have different and less noble purposes, but the goal of this study is progress and sustainability for society.

At this point, we note that this model still has quite limited expressiveness. It lacks any description of the context and a measure of the quality that can be associated with the state in order to rate or assess the behaviour of the agent during the process. The metrics than can be used are numerous, but here we will focus on the sustainability of the interactions. Good progress should aim to maximize these kinds of metrics.

Thus, we need to augment the state **s** from a triple to a four-tuple by adding a parameter q to assess the amount of good progress achieved by the interaction in that state. However, the addition of this extra attribute is still not sufficient for an effective modeling scheme. In order to make the *AE process* more semantically determined, a further attribute should constitute the primary key in order to relationally associate a name or other descriptions or semantics to a certain state **s**. The major aim of this new attribute is to

name and track the evolution of the *AE process* through its states; a natural name for it is d, standing for *description*.

We have come up with a fifth-tuple in order to provide enough expressivity to the attribute set of the state **s**, namely, $< a, e, i, q, d >$.

With this setting, a transition table can now be used to formally describe the automaton associated with the *AE process*, like in the following example of Figure 3.

Transition tables determine how state changes depend on a transition t. For example, in Figure 3, if we start with s_0, depending on t assuming a value of *Completed*, *Interrupt*, *Fail*, or *Rejects*, the next state will be s_1, s_1 (a loop), s_3, or s_4, respectively. If the empty state $\emptyset$ is targeted, it means that in that state the event *Progress* has no effect.

state \ t	*Completed*	*Progress*	*Interrupt*	*Fail*	*Reject*
s_0	s_1	$\emptyset$	s_1	s_3	s_4
s_1	s_5	s_5	s_1	s_2	s_1
s_2	s_1	s_5	s_2	s_2	$\emptyset$
s_3	s_1	s_0	s_0	s_0	$\emptyset$
s_4	s_0	s_1	s_1	s_1	$\emptyset$
s_5	s_6	s_7	s_5	s_5	s_1
⋮	⋮	⋮	⋮	⋮	⋮

Figure 3. An example of possible transition table for the formal description of the *AE process*.

Note that the one in Figure 3 is "almost" the simplest form of automaton, namely, a nondeterministic finite automaton (NFA). Automata are used to straightforwardly produce a software that can simulate and handle the evolution of the *AE process*. In practice, an NFA is a synthetic description of a process, but it does not allow a direct physical implementation. A nondeterministic model is used when more than one transition is possible from the same state. For example, if we consider the first row in the transition table of Figure 3, from s_0 are four possible transitions to other states. In the NFA, there is no detail about the logic that causes one transition with respect to the other. However, in this case, the implementation is obvious, with a *switch case* that senses the event t.

Usually, a conversion is made into an equivalent deterministic finite automaton (DFA), which can be prone to deterministic physical realization. This transformation is a well-known practice in automata theory and does not present particular difficulties concerning optimization and efficiency.

In Appendix A, a friendlier, intuitive, and equivalent representation of the transition table is given.

Another possible representation is the use of trajectories, as shown in Figure 2, although they are useful only up to three dimensions. If the fifth-tuple of the states are projected into the $< a, e, i >$ triple then the paths and loops could show some patterns useful for analysis or classification of the process.

However, NFAs are often too weak for a process that tends by its nature to evolve and progress indefinitely. Thus, with this example, we have limited ourselves to giving a perspective. Other types of automata, e.g., nondeterministic, with infinite states or ω-automata, will prove more appropriate in many cases. Beyond that, processes of a stochastic nature, where transitions occur with some probability, can be modeled with structures such as probabilistic automata or Markov Decision Processes.

The fundamental thing here achieved is the definition of the state space. With this, it is possible both to analyze and then control how the *AE process* evolves and how and when it crosses states where the context of Hybrid Reality, and thus the HyR model, is

relevant. Process mining, and possibly some predictions, are enabled by the recording of the trajectories of the *AE process* in the *AE state space*, as achieved with the formalization in this section.

3.3. The Cybernetics of HyR

If we delve into the framework of cybernetics to find valuable modelling and control tools for HyR, a starting point is that of the law of requisite variety due to Ross Ashby [75]. The problem is that of a regulation that an agent wants to enact in a complex environment to achieve a goal in the face of a set of disturbances that are more or less predictable, uncertain, and unexpected. Regulation has to be understood as a more general concept than control, to include it as a particular case. For a regulator R, the action of an agent is necessary in order to lower the *variety* of the outcomes of the regulated system. Given a set of elements, its variety is the number of elements that can be distinguished.

Agents use regulation to react purposefully to the disturbances that are part of the system. If the agent uses R to act like this, then there is a quantitative relation between the variety of D (the disturbance), the variety of R, and the smallest variety that can be achieved in the set of actual outcomes [75]. The constraint that holds between these varieties is general and is called the law of requisite variety. The law of requisite variety states that the variety available to an agent, which is the range and set of possible actions to choose from, must be as rich as the range of potential disturbances or situations that the agent confronts in order to achieve a purposeful regulation of a system [76]. By means of the expression of the variety in logarithmic form, we obtain

$$V_R \geq V_D - V_A, \tag{1}$$

where A is the set of actions available to the agent and V_A is the logarithm of the number of regulation actions that she/he/it can perform; V_D is similarly related to the number of disturbances that enter the system, and V_R is the variety of the outcomes of the regulator system. In Figure 4, a general scheme of the cybernetic loop that involves an agent and the problem at hand (the HyR environment), under the Law of Requisite Variety and its constraints, is provided.

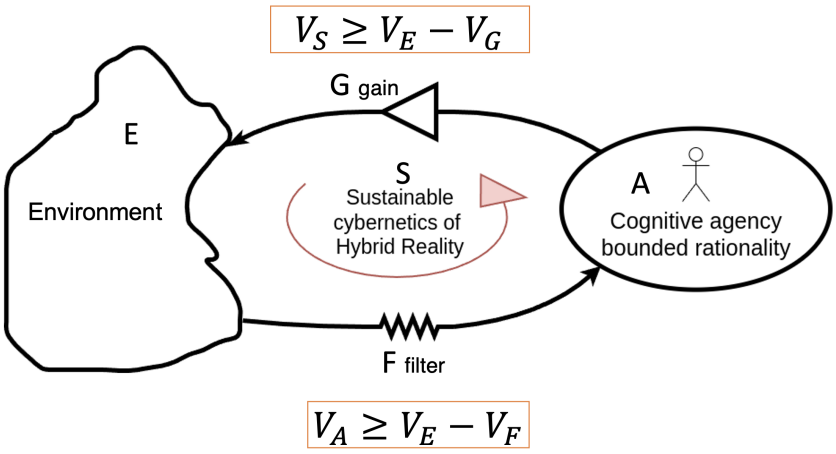


Figure 4. The law of requisite variety applied to the problem of the cybernetics of the Hybrid Reality problem.

This loop is valid in general, not only for the specific HyR problem. Nevertheless, Figure 4 highlights that the agency, both human and artificial, is in the loop of the overall regulation of system S. The agent usually has much less variety than the controlled system needs. Thus, the regulation actions made by the agency have to be amplified with a system

called *G* in order to match the high variety of the environment and its complexity. This is the forward direction of control.

The feedback from the environment is provided through a filter *F* to the agent. The feedback must reduce the variety of the environment in order for the agent to have a viable ground on which she/he/it can act and thrive effectively. This is due to the inherent bounded rationality limits that every agency has to cope with. Note that, in both cases, the filter *F* and the gain *G* have the function of controlling the variety. For the filter *F*, the variety of the outcomes is lowered with respect to the inputs. On the contrary, the amplifier *G* has to produce, as an outcome, more variety than was in the input. Both these effects can be obtained by suitable use of regulators that obey the law of requisite variety. Indeed, regulators are very powerful, universal, and general systemic structures.

4. Resulting Methodology

Having so far fine-tuned the methods available for the HyR model, below we propose a methodology as a result of using these initial positions and as an initial methodological tool of investigation.

The methodology will require going through a new insight that uses the Law of Requisite Variety to design the right components that allow sustainable control and stabilization of the HyR phenomenon. When a state of the *AE process* involves the *AN* quadrant or the *NA* quadrant of the *AE matrix*, we are dealing with HyR. In essence, the problem is to develop a sustainable cybernetics of HyR for each of these cases and in the interaction between agents and their environment, as pictorially described in Figure 4.

Once the focus has been achieved for any of the affected states, a systematic engineering procedure must be constructed to allow the HyR stabilization process to be repeatable and consistent. In this way, the method of SD is used to achieve a dynamic model that can be used as a "flight simulator" for the engineering process involved in the construction of the overall HyR stabilization control.

This systematic construction will show the relevance of the use of a set of technologies (more or less mature) that are available in the framework of BC. It will be evident how this toolset gains a primary role in the practical development of a suitable controlled interface between humans and artifacts, as required by sustainable HyR.

Before delving into the details of each step of the methodology, it is advisable first to provide the big picture of it by means of a flowchart, as given in the next section.

4.1. Definition of the AE Workflow

In this section, a workflow is defined as a systematic procedure that renders the application of the proposed methodology systematic. This workflow is named the *AE Workflow*. The flowchart in Figure 5 is created to determine an algorithm that constitutes a meta-level framework that applies the steps of the methodologies in ordered and systematic steps. The processing performed in the flowchart are substantiated by the methodological steps described in the following sections.

It starts with the construction of a state space and a related automaton to keep track and a record of the transitions across the states. In case a former history is available, the state automaton can start from a known point of a trajectory in the state space. Trajectories in the state space allow for analysis of the *AE process* as well as some predictions and inferences about decisions to make for the future developments of the *AE process*.

The current state is processed until some event occurs that would force a state transition. Depending on the landing state, if HyR stabilization is required, then all the steps of the methodology proposed here will be conducted. Otherwise, in the case that the *AN* or the *NA* quadrants of the *AE matrix* are not involved in this state, an information system

simply might record the processing of such a state to make sure that the information on *AE process* does not have holes in it anyway. This record becomes a crucial datum to be used in case a systems engineering process is needed to synthesize a good adjustment for HyR stabilization, as in Figure 4. The stabilization process is necessary and iterated each time the interaction between agencies and the current environment belongs to the *AN* and *NA* quadrants of the *AE matrix*.

In the next section, Section 4.2, the SD of the HyR is introduced as first central step. From that step, the design and synthesis of filter and amplifiers for the HyR stabilization are conducted as explained in Section 4.3. Finally, the important role of BC technology components is introduced to complete the methodology in Section 4.4.

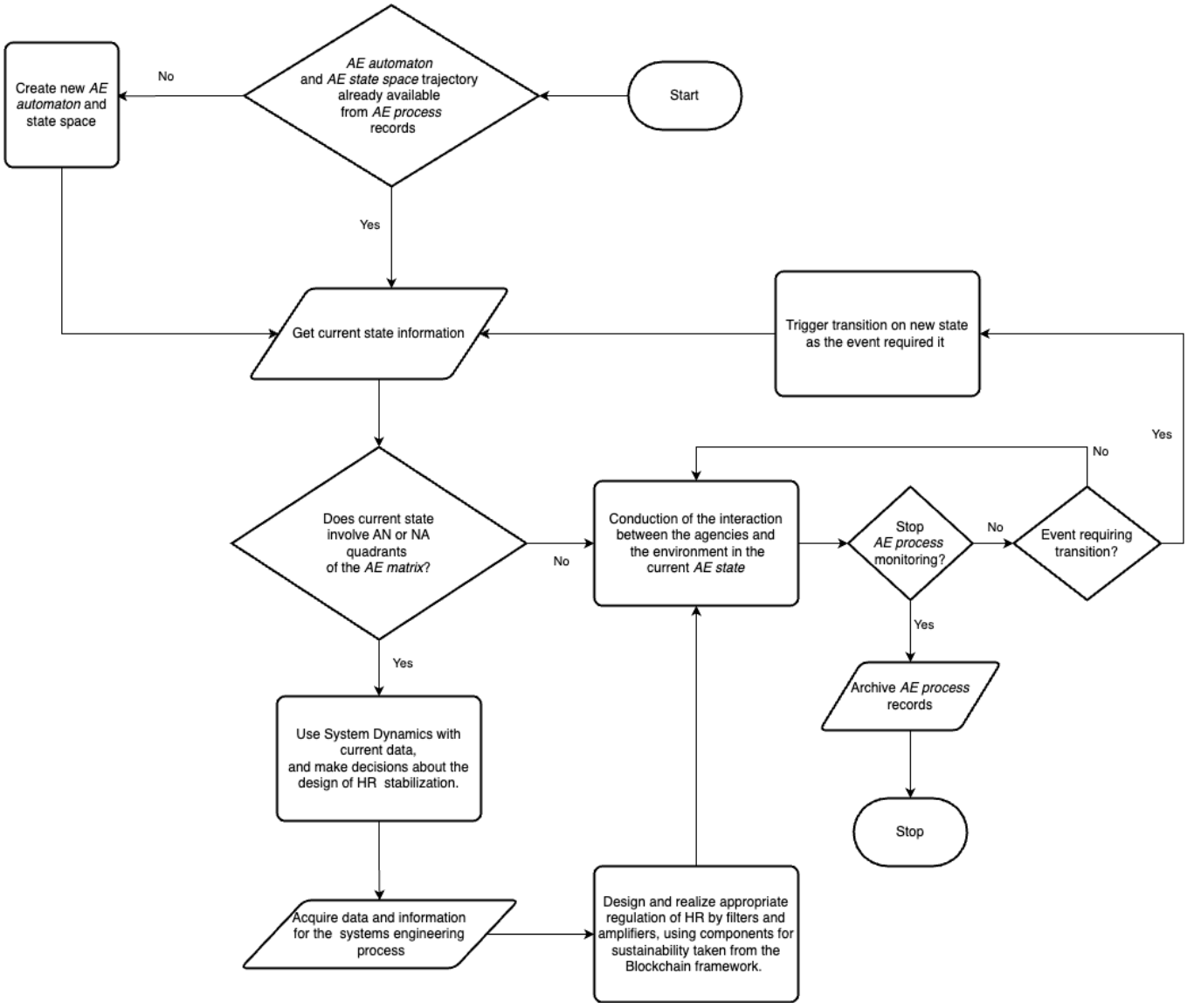


Figure 5. Workflow of *AE process* modelling and control.

4.2. System Dynamics of HyR

In the previous section, a systemic procedure was introduced that aims to simplify and decompose the problem of realization of the filter and amplifiers for the stabilization of the cybernetics loop for any HyR problem. Nonetheless, the focus and the challenge remain on the actual design and synthesis of *G* and *F* systems to gain control over the interactions that human or artificial agencies (*A*) perform with a natural or artificial (e.g., digital) environment (*E*).

A causal loop diagram (CLD) can help in visualizing the dynamics involved in the choice and harmonization of the components that collaborate and co-evolve in creating the technology that aids in the engineering of the filters and of the amplifiers of the *S* loop (see Figure 4).

Following a model-based systems engineering (MBSE) approach, human (or natural) and artificial subsystems, which constitute the realization of *F* or *G* systems, can be considered as a library of functional packages that can be simulated and composed for control synthesis. To distinguish this new approach from the usual MSBE, here, HMBSE (Hybrid MBSE) is coined to highlight that the components can be natural or artificial.

The CLD is a powerful tool for modelling the dynamics involved in the construction of such a control system. Having posed the ground, it is important to assess the dynamics that occur in the HyR system, as in Figure 6. The graph has been obtained with the Vensim® software tool, which is widely used for modeling. We refer the reader to the tool manual for a complete understanding of all the graphic elements in Figure 6 [77]. For a gentle introduction to System Dynamics (SD), we suggest the reader to refer to [78,79]. The arrows in the diagram indicate causal relationships between variables in the model. The positive (+) signs at the arrow heads indicate that the effect is positively related to the cause, while the negative sign (−) indicates a balancing negative effect. For example, in Figure 6, the more *Unknown & unexpected events* we have in this system, the higher demand there is *G* and *F* variety increases. At the same time, the more *S stability* is gained, the less demand of *G* and *F* variety is implied. By composing these causal chains, 16 causal loops are identifiable. If a loop is self-reinforcing (positive feedback effect), it is marked with *R*. If it is a balancing (negative feedback effect) causal loop, it is marked with *B*.

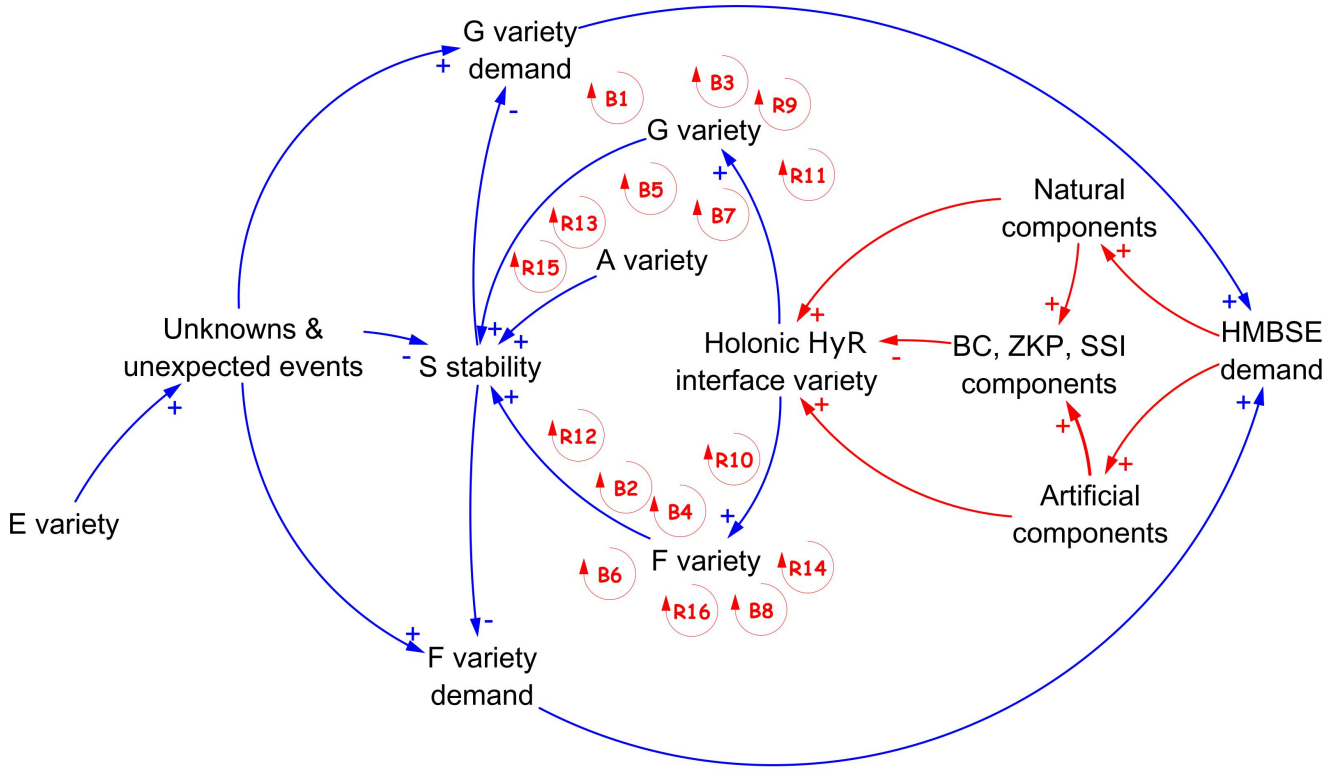


Figure 6. System dynamics of the HyR cybernetics: a CLD of the HyR cybernetics.

In Appendix B, more details on the CLD exemplified here can be found.

A further method in SD is the Stock and Flow diagram (SFD). This will be more effective for achieving the simulator for the dynamics involved. The difference between the two methods can be found and is effectively discussed in [4]. For the scope of this proposal,

CLDs are the first necessary and useful step, but always a complement and propaedeutic to other methods of SD.

The CLD in Figure 6 expresses the causal relationships between the elements that are needed in order to let the *S* system be stable, viable, and sustainable. The variety of *E* is the source of unknowns and unexpected events for the agents that try to control it. The disturbance provoked by these events hinder stability and trigger a demand for the active parts of the cybernetic loop. This, in practice, means that there is a new demand for the design and realization of appropriate *G* and *F* systems. They have to be designed almost simultaneously—namely, the filter on the feedback edge *F* and the amplifier of the agents' actions *G*. Both *F* and *G* demand, in turn, cause an HBMSE process demand in order to synthesize the due control devices. The HBMSE will be based on a suitable combination of natural and artificial components—"suitable" is the real problem.

An important insight is that the involvement of natural and artificial agents in system control necessitates an ethical filtering mechanism, ensuring that decisions are certified, traceable, and trustworthy. The BC framework offers robust tools for this purpose. As the autonomy and intelligence of agents increase, so does the need for rigorous filtering. Both human and artificial agents must operate under the same BC-based accountability infrastructure, which serves as a common trust foundation.

At the same time, in Figure 6, holonic HyR is mentioned. An assessment on the perfect mix of the natural and artificial components in the design of the control (*F* and *G*), is made by a holonic paradigm. Holon is an entity that manages the interface between the artificial and natural realms [6,7,45]. The holon is a fundamental element when two irreducible aspects of a phenomenon are in place simultaneously. Typically, this involves the coherence between parts and wholes of a system, with a complex set of relations that could not be expressed by closed-form expressions of mathematics. Even in the case of such complexity, certain engineering and implementation solutions can sometimes satisfy the problem, such as relying on emergent behavior mechanisms [6].

In Section 4.4, it will be shown how the mix of technologies provided by the BC framework is something that introduces aspects of ethics, sustainability, and cybersecurity. With these kinds of tools, the burden on the holonic system from a sustainability perspective is reduced. We consider it a necessary step when a multi-agent systems solution is used to address the synthesis of *G* and *F* (as explained in Section 4.3). The variety of the interface to the holonic HyR layer is in turn reflected in the variety of *F* and *G*. The higher the variety of *F* and *G*, the more effective the control towards the stability of *S* will be [80]. The stability of *S* benefits from the given amount of variety in the *A* (agent) system, but is hindered by the variety of unknown and unexpected events that happen in the problem environment *E*.

The CLD developed here is not unique and definitive, as in the spirit and foundation of the SD discipline itself. Nonetheless, the one proposed here considers in the model all the essential elements necessary to draft a systematic procedure that involves, as a whole, the law of requisite variety, the holonic approach, the HMBSE methodology, and the very important BC framework, as detailed in more depth in Section 4.4.

4.3. Regulation of HyR Through Law of Requisite Variety

As seen in Section 3.3, the Law of Requisite Variety is the foundational ground for the control of the cybernetic loop that aims to stabilize the conditions in which the interaction of the agency and the environment happens. This is essentially achieved by designing appropriate and balanced means of amplification and filtering in relation to the respective varieties.

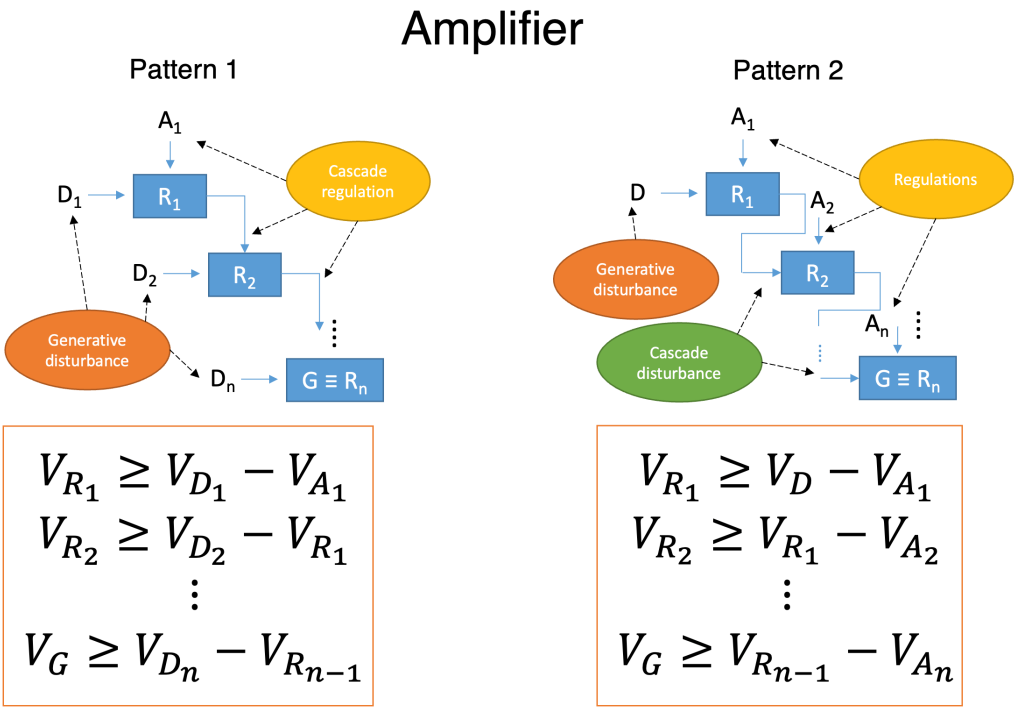
The twist proposed here is that the realization of filters and amplifiers can be achieved with an appropriate configuration of a set of regulators. As the Law of Requisite Variety is

defined in detail for regulators, the use of regulators as the only type of component allows a direct use of the Law of Requisite Variety. This is a normalization into a canonical form of amplifiers and filters.

With this canonical form available, the design and realization of amplifiers and filters in the *S* loop can be achieved by using two recurrent and alternative patterns that make use only of regulators as components. These patterns can be used both for filters and amplifiers. This is shown in Figure 7 and Figure 8, respectively.

The difference between the two patterns is in the nature of the disturbance, the actions, the outcomes of the regulators, and how they are connected. These patterns allow a general decomposition of the problem into lower-order problems, but retain parts and wholes at the same time under a holonic perspective where necessary.

It turns out that this type of decomposition is a usual practice in systems engineering, where pragmatic holism is required while problems are attacked with a reductionist and hierarchical approach to reduce complexity [81]. In our case, some kind of closed form of the decomposition connects in a quasi-additive way the role of components to the variety of the whole. Nonetheless, the weak form of the law of requisite variety, which is an inequality, needs a holistic comprehension of the whole that cannot uniquely be derived from a sum of the parts. Eventually, this decomposition retains some form of complexity in the system. This is a feature for this kind of system as the complexity that the controlling system retains "absorbs" the complexity of the whole problem. This can be considered a variant of the law of requisite variety—the "Law of Requisite Complexity".



$$V_{R_1} \geq V_{D_1} - V_{A_1}$$
$$V_{R_2} \geq V_{D_2} - V_{R_1}$$
$$\vdots$$
$$V_G \geq V_{D_n} - V_{R_{n-1}}$$

$$V_{R_1} \geq V_D - V_{A_1}$$
$$V_{R_2} \geq V_{R_1} - V_{A_2}$$
$$\vdots$$
$$V_G \geq V_{R_{n-1}} - V_{A_n}$$

Figure 7. Patterns of realization of amplifiers that use regulators as constituent components. Pattern 1 was realized with a cascade of regulators' output while Pattern 2 shows a controlled cascade in the disturb inputs. The relative expressions abiding by the Law of Requisite Variety are shown for both patterns.

In the case of amplifiers in Figure 7, Pattern 1 is constituted by a cascade that uses only one regulation input from the agent. Then, the subsequent regulations are achieved by wiring the outputs of a regulator as the input of another. In this way, the variance of the cascade would ideally tend to decrease the variance of the agent, in the absence of any contribution of the disturbances; variance amplification would not be possible in this

way. However, if a well-forged disturbance is applied at each regulator stage, the resulting variance will increase and at the same time be controlled. Generative techniques can be used, making use of AI as well as classical control systems and engineering theory. The generated disturbance should also whiten (in the Gaussian signal sense), and so reduce, the unavoidable disturbances that come from the physical realization of regulators.

With Pattern 2 for amplifiers, the unique source of independent disturbance is taken at the first stage. The generative disturbance *D* can also be used in this case to manage the unavoidable disturbance introduced by the physical realization of the first stage. Subsequent disturbances are to be indirectly addressed with a cascade of the outputs from the regulators. In this case, the agency could be able to act independently at different stages of the regulators with suitable regulation actions. By forging appropriate regulation and corresponding varieties, the overall effect is that of a controlled amplification of the final variety of the output, which has to cope with the bigger variety of the environment E that the agency A has to keep up with (see Figure 4).

In the case of filters, in Figure 8, the overall effect should be that of a reduction in the variety coming from the environment *E*, in order for the limited capability of the agency to be able to cope with the variety (of information) that it can obtain from the environment, in the form of feedback to the actions made. The effect is an overall attenuation in contrast to the amplification seen above. Authors like Beer [82–84] preferred to use the concept of *attenuation* instead. Nonetheless, here we prefer to express it more as a filtering effect, in order to focus on the signal processing and information processing that are implied in the reduction in variety. This is also to conform to the modern trend whereby most signal processing today falls under the umbrella of machine learning and is part of what is considered AI technology.

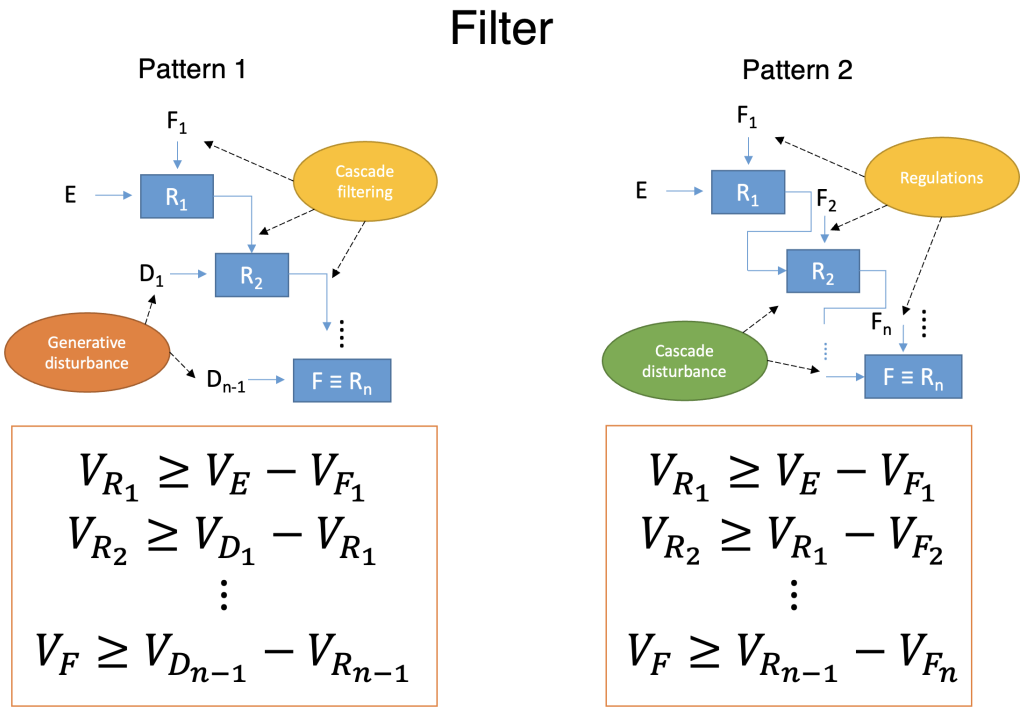


Figure 8. Patterns of realization of filters (attenuators of variety) that use regulators as constituent components. Pattern 1 is realized with a cascade of regulators' output while Pattern 2 deals with a controlled cascade in the disturbance inputs. The relative expressions abiding by the law of requisite variety are shown for both inputs.

In Pattern 1, the variety of the environment E is fed as disturbance at the first stage. Other disturbances can be put under control even in this case with some generative synthesis of the signals that can whiten, and thus tame, uncertainties and variety. The filtering is enacted once at the first stage, and other stages are fed with the outputs of the regulators in the cascade.

Pattern 2 for a filter is the more natural realization for it, although in principle and under some conditions, Pattern 1 becomes a useful alternative. In Pattern 2, the environment is still seen as a disturbance but, in this case, the filtering can be achieved at many stages, while disturbances are coming from the output of the regulators. In this configuration, the agency has the opportunity to act independently with a set of filtering actions.

Table 3 presents a set of exemplifying use cases that facilitate the understanding of how the previously introduced filter and amplifier patterns can be applied in well-known practical scenarios. It is important to note that, when transitioning from contemporary approaches to control and regulation—commonly employed in control systems and engineering disciplines—to the regulation framework rooted in cybernetics, as depicted in Figures 7 and 8, the correspondence may not always be immediately apparent. In this context, the implementation of control and regulatory mechanisms should be considered as an inherent and integrated component of the regulation input provided by the agency at the regulator stage.

Table 3. Use case examples of amplifiers and filters according to different design patterns.

Regulation Type	Pattern	Use Case Example
Amplifier	Pattern 1 (Figure 7, left)	Current generative pre-trained transformers (GPTs) can provide a human agent with more information than they have at the beginning of an inquiry. In this case, the agent is learning something from the environment, which is the digital information available to the GPT. In this learning interaction, the agent devises a prompting scheme that can be seen as a cascade of regulators that amplifies the variety in two steps. The data resulting from the first inquiry (R_1) are cascaded as input to the second stage of the prompt (R_2). D_1 and D_2 give the incremental generative information that the GPT produces and that is regulated by the agent's prompting skills. For example, the agent instructs the GPT that after first inquiry, like "find me references about projects on food supply chain," it then should execute the following: "Without waiting for further user input, the assistant anticipate what would be useful next, with tabular comparisons of the references obtained in the first inquiry".
	Pattern 2 (Figure 7, right)	An example might be a cascade consisting of the accelerator pedal and the steering of a car. The generative disturbance D is the motor power available. At a first stage R_1, the agent chooses the A_1 input level. The output is a linear forward movement that, as a disturbance, must be regulated by a steering action A_2 on the steering system of the car.
Filter	Pattern 1 (Figure 8, left)	In almost all the applications for video call conferences, today it is possible to select a fancy background to apply to the speaker's image. In this case, the E is the full video signal. F_1 is the action for selecting the speaker's contours in order to extract the foreground image from the background. Through the identification of the contours as output of R_1, a second regulation stage R_2 provides Gaussian noise (blurred background) from a pseudorandom signal generator as D_1, and applies it only to background, having received in the input the contours of the part of the image that must be passed untouched.
	Pattern 2 (Figure 8, right)	A typical use case is that of a passband filter for processing radio frequency signals. The first filtering action F_1 may perform a low-pass filtering of the E signal at regulation stage R_1. The output is sent as disturbance to the regulation stage R_2 and filtered with a high-pass filtering action F_2.

4.4. Role of the Blockchain Framework

The role of the BC framework is fundamental in creating and controlling the contact point between the natural and the artificial. And this is the very zone of intervention of HyR. When the *AN* and *NA* quadrants of the *AE matrix* are involved, the contact point emerges as being a critical one—and also little studied so far.

The BC framework offers a foundational concept for handling the interface between natural and artificial agents through the notion of an *oracle*. Potentially acting as a dual-direction *oracle*, BC notarizes human actions according to a trust model on the natural side, and ensures the transparency and immutability of artificial actions in the other direction. It also enables post hoc analysis for greater explainability of AI-driven decisions.

The Oracle and Reverse Oracle patterns [12], enabled by smart contracts (e.g., in Ethereum), address the interaction between BC and the external world. Oracles allow BC to receive trusted external data, while Reverse Oracles enable off-chain components to react to BC state changes. Despite inherent uncertainties, these patterns offer the most effective current approach to regulating the interface between natural and artificial domains.

Concerning the privacy and the ethics associated with this problem, the ZKP (Zero-Knowledge Proof) framework provides suitable solutions, though still with some technical limits that research is trying to overcome [85]. The amount of private and sensitive information shared in the context of a digital communication (e.g., Internet) increases with the amount of digitalization. This means that there is a growing need for solutions to protect and regulate this information. Within the ZKP framework, the content of a transaction between two entities can be hidden, while proof of correctness and authenticity is provided at the same time. This means that all the agents participating in a network of communications can trust all the communications without knowing or disclosing their content [86].

Trust among agents can be enhanced through heterarchical identity systems like Self-Sovereign Identity (SSI) [87], which grants agents full control over their personal data and its disclosure. SSI eliminates central intermediaries, enabling agents to present identity claims and credentials securely and directly. It is complemented by ZKPs, which provide a supporting infrastructure for privacy-preserving implementations [51].

Figure 6 illustrates how the role of BC is a central means for the sustainable integration of components coming from the natural and the artificial side. An AI application is, in this way, forced to abide by strict trustable and privacy-preserving protocols, as well as to avoid situations where a natural entity abuses artificial tools. Both of these agencies cannot escape auctions and control on the goodness of their actions. They can be banned from the system or network even in real-time and based on some well-designed smart contract.

In the perspective just discussed, we can consider the set of technologies currently available to us as a useful Cybersystemic toolbox. This leads us to formulate an all-encompassing definition of this set of tools, which we refer to in its entirety as the *Cybersystemic Security Kit*. With this definition, we also intend to include other technologies within the BC context that, for the sake of brevity, have not been directly mentioned here, or that may emerge or develop in this context in the near future.

In Table 4, a summary perspective on the role of BC framework is provided with respect to the HMBSE that is elicited in the *AE process*.

Table 4. Summary of the role of BC technologies in the context of HMBSE for HyR.

Technology of BC Framework	Maturity Level (for Relevant Intended Purposes)	Essential Background and Description	Use in HMBSE
Smart Contract	Medium. Smart contracts are a rather mature technology. They can reliably be used although still research is ongoing on their security and scalability [88–96].	Smart contracts represent an automatic programming framework executed even among untrusted parties by eliminating third parties. Smart contracts are containers of code that encapsulate and replicate the terms of real-world contracts in the digital domain [88,93].	Contracts are fundamentally a legally binding agreement between two or more parties, with each party committed to fulfilling its commitments. The interface between HMBSE components becomes trusted and sustainable with this technology [90,94,95].
Oracle	Low. There are still open problems in this technology and research is ongoing [11–21].	Oracle and Reverse Oracle are patterns that enable communication between on-chain smart contracts and off-chain components [12,15]. The open problems are the trustworthiness, sustainability, and scalability of these operations [11,13,14].	Accuracy and trustability of data across the transactions that the components of the HMBSE should be preserved with the Oracle and Reverse Oracle. With these technologies, the actors (human or artificial) in the system gain and preserve reputation [14,16,17].
Zero-Knowledge Proof (ZKP)	Medium. The technology has many variants and tools available [85,86,97–101]. Nonetheless, still, the non-interactive proof in general bears high computational costs and limitations [99].	ZKP is a method by which the prover can prove to the verifier that some statement is true without revealing any information other than the fact that the statement is true. This process can be made non-interactive and succinct in many but not all cases [85,97,99].	ZKP is essential for actors and components in the HMBSE to prove their correctness and trustworthiness while retaining privacy, secrecy, and autonomy. Documents and computations can be verified. ZKP is the key enabling technology for others like the Oracles and SSI [10,99–101].
Self-Sovereign Identity (SSI)	Medium. It is a very promising and well-investigated technology, as it is an acknowledged game changer for many distributed privacy-preserving and democracy-driven applications [87,102–104].	SSI allows actors to be the only owners of their data and to decide what to share and in which granularity; they can only share the minimum amount of information that is needed for their or societal benefit [51,87,102,103,105].	In the search for sustainability, the actors in the system would be allowed to retain ownership of selected part of their credentials and at the same time provide a strong but democratic system of role-based access control on information for decision making [51,105,106].
Tokens	High. Fungible, Non-Fungible, and Soulbound Tokens are well supported today and they can be efficiently included in applications that feature smart contracts [10,105,107–113].	Tokens are digital assets representing ownership, value, or utility within a BC ecosystem. They are created and managed typically using smart contracts, and can serve various purposes like cryptocurrency, utility, security, non-fungible uniqueness [109], and identity, credentials, or personal achievements [107–112,114].	Tokens are an essential feature when it comes to recording, exchanging, transferring, or retrieving values or credentials from any actor in a collective system. They are key enablers in reputation and value creation systems [105,107,114].

5. Seven Steps of the Methodology for a Use Case

In this section, we will give a brief example and a taste of how the methodology is intended to be applied in practical cases. As anticipated in the introduction, our guiding case comes from a food supply chain research project (as recalled in Section 5.1).

At this time, it is not possible to provide data or experiments, but we at least show the reasoning and criteria that can be used to apply the methodology in a case study. This is with the primary purpose here: materializing abstract and high-level discussion of methodological components. The methodology of Section 4 can be conveniently decomposed in seven major steps, as a first approximation. In the following, each of these steps are confronted with a use case in order to illustrate the workings of this methodology.

5.1. An HyR Scenario in Supply Chains

Awareness of the existence of HyR problems, in the supply chain context, came from the execution of research and innovation activities in an EU project (ENOUGH project, grant agreement ID: 101036588) [3]. The EU-funded ENOUGH project aims to holistically improve strategies in the Farm-to-Fork context by creating new knowledge, technologies, tools, and methods to enable the sector to reduce GHG emissions by 2050.

The overall aim in the project is to organize a food supply chain in order to pursue a continuous improvement of this system with the objective of the lowering of GHG (greenhouse gas) emissions. In the ENOUGH project, complexity is expressed in many ways and dimensions. The first is the technological dimension, where the digital transformation of the processes is a rapidly growing trend in the context of Industry 5.0. The second is in the economical dimension, as sustainability aspects are closely connected to the economic models applied to businesses. The third is a societal dimension, as both technology and economy have to be harmonized for the good of citizens and workers. In contemporary EU frameworks, there is a concerted effort to simultaneously address all of the United Nations Sustainable Development Goals (UN SDGs) [9]. Within this context, AI (artificial intelligence) and BC technologies are expected to play a central role, alongside the full array of innovations, regulatory provisions, and challenges inherent to the transition toward Industry 5.0 [115,116].

The interface across the agents in the problem of the regulation of a supply chain is given by the Choreography diagram of the Business Process Model and Notation (BPMN) specification in [117]. The OMG's BPMN 2.0.1 specification has been published as International Standard ISO/IEC 19510:2013. BPMN Choreography provides a notation that is readily understandable by all business users: from the business analysts to the technical developers responsible for implementing the technology that will perform the relevant processes, and finally, to the business actors who will manage and monitor those processes.

The technology adopted in the ENOUGH experimental setting is a mix between the RMAS (Relational-model Multi-Agent System) and the BC framework comprising ZKP, zk-Rollup, Fungible Tokens, and Non-Fungible Tokens. An account of the approach under investigation is available in [10]—we have defined here the set of these BC-related technologies as the *Cybersistemic Security Kit*. For more details on the RMAS, see Pirani et al. [118,119] and references therein.

The overall framework derived on the RMAS and the related platform is called the SDS (Smart Data System). The SDS infrastructure allows human and artificial agents to exchange data and information on an event-based mechanism [10]. The SDS infrastructure supports both a typical DCS (distributed control system) and a decision-making layer. The agents are nodes in a network, and the SDS is considered just another peer in the network. Just like any other node, the SDS has to participate in the overall trust in the network while

providing services and interconnection as a hub. All the nodes are connected by these means of communications with a Publish/Subscribe scheme.

Over the Publish/Subscribe infrastructure layer, the SDS provides a semantic layer and view. Such a view is that of the choreography of the nodes, designed in order to pursue purposeful organization as a whole, constituting the main view of the supply chain.

Within a scenario like this, a primary challenge in the SDS is the behavioural definition of a BPMN Choreography activity, which is shown in detail in Figure 9. All information about the private, possibly hidden, internal process executed by the *Initiator* is used to produce the content of the public message sent to the *Recipient*. An important transformation takes place between private information and public data, however enclosed in the information environment of the supply chain. This is an important first interface between two realities, one of which is predominantly natural and private and the other digital in nature.

Only selected, publishable data are disclosed by the *Initiator*, which withholds sensitive information. This role—human or machine—is functionally identical within the BPMN Choreography. The key challenge is ensuring that disclosed messages accurately and reliably reflect the underlying hidden process that generates the message. Here, BC technologies provide a trust-preserving interface between private and public domains, enabling actors to verify actions without exposing sensitive data. Zero-knowledge approaches further support this by allowing trust without revealing private details.

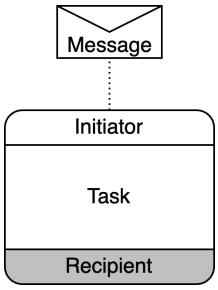


Figure 9. Detail of BPMN Choreography activity.

The supply chain is a clear case of HyR, where human and artificial actors collaborate, often requiring private, local data to remain hidden while ensuring global verifiability. A key issue lies in the hidden private processes behind public message exchanges. These must remain private while ensuring mutual trust. For example, automated quality control systems depend on human-provided inputs, and faulty data can compromise downstream processes. Thus, artificial agents must "trust" human inputs in an abstract sense. This scenario involves the *oracle* problem, which BC technologies aim to address [11–21]. While partial solutions exist, BC alone may not be viable across all supply chain stages due to limitations in cost, energy, and adoption. Moreover, BC is not the only available trust technology [120]. As noted by Kopanaki [121], supply chains require a socio-technical approach, as IT infrastructures function as complex technological ecosystems, and their resilience to unforeseen events remains an open challenge.

Real-world experimentation in sustainable supply chains is underway to test the proposed perspective. Supply chains, as complex socio-technical systems, naturally manifest the HyR challenge amid ongoing digital transformation.

5.2. Envisioned Steps

Having in mind the scenario of the previous section, we can envision the steps leading to a first implementation of the proposed methodology.

5.2.1. Step 1: HyR Process Modeling

The first step concerns adopting the definitions provided for HyR in Section 3.

According to the *AE matrix* and the related *AE space*, the initial state involves an *NN* interaction between the owner of the SDS platform business and the stakeholders who will become (or own) the agents participating in the supply chain environment. This first type of interaction corresponds to a *Learn* action, used to acquire specifications and information for constructing the contracts that stakeholders commit to in order to participate in supply chain operations.

The outcome of this interaction is then the development of the BPMN Choreography that constitutes a holistic and collective view of the supply chain. The owners of the SDS platform will *Use* this software to create the BPMN Choreography configuration—thus, they will interact in an *NA* state. The software in this case is already available, and no particular engineering action is expected, and no particular issue of sustainability is expected. Therefore, no specific cyber-systemic design is required. In general, though not always at first, ergonomic and usability issues may arise for the agent using the software, requiring a redesign of the software.

In using the software to configure the supply chain scenario, any activity in the BPMN Choreography (see Figure 9) has to be detailed. At this point, challenges arise because the BPMN *Initiator* actor wants to limit disclosure of their local process while still providing enough public data to the *Recipient* actor to support the collective choreography. Thus, the SDS owner may be subject to receive a *Progress* event in order to proceed to another state. In the new state, a decision may require some specific design choices in order to find an equilibrium. We are now in a new *NA* state, where the configuration design requires the *Initiator* actor to query its information system to find a solution to the problem of privacy for the *Initiator*. The environment in this case will be the huge data available from the information system and the agent is the responsible person (or team) that makes this configuration decision.

According to the workflow in Figure 5, the completion of the interaction in this state can take advantage of the other methodological steps with a jump to Section 5.2.2.

Nonetheless, before delving more into next steps, we recall that the set of the interactions constitutes the state space, and the trajectories in the state space create a trace that can be analyzed and used as input to the automaton that determines the workflow of the Agency–Environment process. This trace, as well as the model and the state space, are constructed, as just done, on the fly; but there can be situations in which a state has been already visited in the past, and so it is just repeated, and possibly updated.

The number and granularity of the states can be huge. Thus, although not explicitly mentioned here, to keep things simple, a hierarchy of *AE processes* in many cases is needed, with a recursion of the *AE workflow*. Recursion and self-similarity represent the major approach in the face of complexity in general. This has been studied since the Viable System Model of Stafford Beer [82–84,122]. More recently, the role of holonic architectures has taken on a similar importance for management in the industrial playground [45,123], even considering the integration of the Viable System Model with holarchies [124].

5.2.2. Step 2: *AE Workflow* Execution

In this step, the intended interaction is conducted and executed according to the *AE workflow*. In this step, all the information available to the *Initiator* is considered in order to proceed or not to other steps.

In the running example from the previous section, the current state involves an HyR situation, in particular that of the determination of a *Create* action for the *Initiator* in order

to develop a solution for the problem at hand. This seems to require a decision that will involve all the other parts of the methodology downstream.

One consideration for this step is that, in the case where process modeling is carried out on the fly, this step tends to coincide with step 1. In contrast, it remains clearly distinct in the case where the execution of the workflow occurs on a process that is already to a large extent a priori defined and that has its state space.

In the specific case of this example, the third step is now promptly invoked.

5.2.3. Step 3: Cybernetics of HyR

This step involves the application of Ross Ashby's law of requisite variety and the method of Section 3.3. Making reference to that discussion and to Figure 4, here, the model of the current interaction is constructed in terms of variety of the environment E, of the actor A, and the expected levels of variety of the G and F elements that will bring S into equilibrium.

To make things more practical, we imagine that the *Initiator* in this case is a transport company. This actor has to assess the quantity of information about fleets, routes, costs, and so on—other aspects of this process. This is grossly assessed in comparison to designing a suitable filter F that aggregates and suppresses sensitive data to produce a public message useful enough to the *Recipient* actor to coordinate purposefully with them. Overall, the variety of this problem environment is V_E and the actor has a much smaller variety of V_A to cope with this problem until it is solved with some appropriate system design of G and F to match and control the varieties in play.

Once the problem is identified and defined under a cybernetic perspective, the SD methods can be invoked in the next step.

5.2.4. Step 4: System Dynamics

Once the cybernetics of the current interaction is clarified, the fourth methodological step is to invoke SD methods. In this article, we proposed an initial example, neither exhaustive nor complete, in Section 4.2 and Figure 6. Nevertheless, the tentative CLD provided is rich enough to involve all the procedural and technological steps and components foreseen in this discussion. In the specific scenario, the *Initiator* assesses the information technologies available (and affordable), as well as the meaning of "sustainable" for the specific realm. In the example, the transporter actor that may want to preserve privacy on some parts of the process; unknown and unexpected events are possible information leaks or fakes that other actors may receive. The proposed *Cybersystemic Security Kit* enables such hidden elements to become trustable unknowns, maintaining privacy and autonomy. On the broader implications of "unknown knowns", see Lee [125]. Nevertheless, it is not said that all the elements appear as an explicit instance in the CLD, and they can be considered as constants that do not provoke causal differential effects in the loops in certain simple cases.

The study of the dynamics of the system during this interaction is used to assess the extent and nature of the components of the design for the solution that have to be balanced to match the required demand of V_G and V_F varieties.

This step assesses the effort, nature, and cost of the F and the G systems to be realized, which brings us to step 5.

5.2.5. Step 5: Realization of the G and F Systems

The output of this phase is the design of the amplifiers and of the filters that bring the HyR cybernetics loop S to equilibrium. Here, systems engineering methods are used to design and realize the amplifiers and the filters according to the regulator patterns explained in Section 4.3.

When the respective structures are designed, it becomes clearer how many and which components will be needed to realize those systems.

Note that this is a step in which SD is transformed into systems design and engineering. It usually requires a big disciplinary jump back and forth between the two. They are tied together here in a systematic way.

In our running examples, the filter output would be a manageable set of information to the actor in order to conduct the design and the creation of the problem solution (e.g., chatbot as design assistant). The amplifier would be a system that traces the transport process, makes predictions, and finds optimal routes for the transport fleet. At the same time, this system should construct a choreography message and a trustable set of data that certifies the quality of the transport service behavior to the other actors in the supply chain.

In this case, the output of this step are design and engineering requirements to be completed within step 6.

5.2.6. Step 6: Choice of System Components

In the sixth step, the solutions are confronted with the choice of a perfect mix of technologies and natural agencies along with the human–machine intermediation provided by the components to be found in the *Cybersistemic Security Kit*.

The step can be materialized in the running example by considering now which design a chatbot technology should use in the filter *F* and which "generative disturbances" should feature in the amplifier's stages in order for the agent to make correct design inquiries and steps. In addition, among these choices, the set of necessary BC technologies is also considered.

For example, if the final solution for the *Initiator* wants to include a generator of verifiable proofs that the process will behave constantly as expected, a system for automatically generating a verifiable ZKP is considered useful. At the same time, an SSI subsystem coupled with SBT would certify that the drivers in the transport fleet have reputation and performance of expected levels, without revealing private information about their identity.

5.2.7. Step 7: Holonic Integration and Recursion

A last step, the seventh, considers the possibility to adopt holonic paradigms in two ways. The first is to harmonize the systems components that are parts into an organized purposeful whole. This is a major feature of holonic entities, in particular when multi-agent systems are used to realize computations.

The second way in which holonic paradigms are of paramount importance is in the decision to raise or lower the level of detail of the interaction model and of the *AE process*. In this case, the holonic paradigm is used for its inherent property of becoming a holarchy (i.e., a hierarchy of holons).

In our running example, having taken the design decision to use chatbots and ZKP, we would like to start a sub-design process to understand better the details of the interactions that are further needed to integrate the two technologies and its feasibility.

In case the level of detail of the current *AE process* model is considered not suitable for practical control of HyR, recursion to a more detailed *AE sub-process* is triggered and step 1 of the methodology is recursively called.

For more detail about relevant recursive techniques and related methodology, we refer the reader to [45] and references therein.

Other recursive models can be used as alternatives or complementarily. The most prominent one in the cyber-systemic area is the Viable System Model [122,124].

6. Discussion, Related Work, and Applications

The methodology achieved in this paper is to be applied in all the cases where it is mandatory to control and regulate the co-existence and the co-evolution of the natural and the artificial, which has been named the HyR problem. The system dynamics of the problem can be now analyzed in more detail if we rely on the cybernetics that is involved. In this section, a discussion is opened to relate the methodological results achieved in this paper with related work.

6.1. Sustainable Cybernetics

What in the previous section, Section 3.3, was called the *S* stability problem, depends greatly on the parameters that give the variety of *E* (the environment) and the variety of *A*, which are given for a specific agent (an agent cannot increase at whim its variety). The actual part in which more degrees of freedom are allowed is the synthesis of the regulation (in particular control) of the system.

The *S* stability problem from Section 3.3 largely depends on the variety of *E* (the environment) and *A* (the agent), which are fixed. The degrees of freedom primarily lie in the synthesis of system regulation, particularly in control.

The increased variety of control, by means of filter *F* and amplifier *G*, can be achieved through various combinations of technologies, devices, and processes involving natural and artificial entities. The challenge is to keep this mix sustainable across multiple dimensions, aligning with the 17 UN Sustainable Development Goals (SDGs) [9]. The concept of sustainable cybernetics has already been well-established in the literature. This study reviews selected works that are particularly relevant and complementary to our framework, though not intended to be exhaustive.

In [122], an integrative concept for sustainable renewal is presented, based on Beer's Viable System Model (VSM). The cybernetics loop of sustainability linked to the law of requisite variety, as in Section 3.3, copes with the capabilities of the VSM and its recursive properties. This creates, by the way, an interesting link with the recursivity that copes with the adoption of holonic approaches, which we introduced among the core elements of the sustainability dynamics in Section 4.2 and Figure 6. Recursive structures are acknowledged as a necessary feature for effective cybernetics [45].

The European Green Deal [126] and the UN SDGs [9] highlight the shift toward a sustainable, circular economy. Research on BC and cyber-physical systems (CPS) shows their potential to enhance traceability, transparency, and resource efficiency [127–129]. Building on these insights, this study proposes a HyR approach integrating BC, cybernetics, and system SD, incorporating adaptive control, knowledge proofs, certification, explainability, and secure identity management for both humans and machines [4].

6.2. A Focus on Ethics and Societal Implications

The proposed methodology and its framework can be considered a complementary work to the systematic process developed by Ashby [76]. The aim was that our methodology would constitute a viable and realistic implementation of Ashby's findings. The proposed methodology complements Ashby's systematic process [76], aiming to offer a practical implementation of his findings. Notably, Ashby's Requisite Integrity requirement can only be addressed today using the BC framework: "*Integrity of the regulator and its subsystems must be assured through features such as resistance to tampering, intrusion detection, cryptographically authenticated ethics modules, and compliance with all laws, regulations, and rules*". In the same line, Requisite Transparency seem the very point of the ZKP framework: "*Requisite Transparency: demanding to be trusted is unethical because it enables betrayal. Trustworthiness must always be provable through Transparency. So the law of ethical transparency is introduced*

[. . .] For a system to be truly ethical, it must always be possible to prove retrospectively that it acted ethically with respect to the appropriate ethical schema" [76].

A key result is the potential to design and synthesize G and F using an integration of natural and artificial tools, enabling sustainable cybernetics for S (see Section 3.3). This introduces a new form of MBSE, integrating BC, ZKP, SSI, AI, and human input in various patterns. The Oracle and Reverse Oracle patterns in BC are central to future research, as they could simplify the interface between natural and artificial systems. The BC framework enables new approaches like NFTs, ZKP for authenticity, Layer 2 for scalability, Smart Contracts for control, and SSI for democratic integrity. These technologies form a complementary mix, enhancing cybersecurity and sustainability in socio-technical systems—namely, the *Cybersistemic Security Kit*.

The *Cybersistemic Security Kit*, seen under the new cyber-systemic perspective provided here, offers new opportunities and tools for the purposeful organization and control of the HyR problem, using a built-in democratic empowerment of the actors (natural and artificial) involved in the regulation and control of HyR systems.

In the case study discussed in Section 5.1, an immutable and transparent record of a product's history enables buyers to verify that goods originate from ethically certified sources. Additionally, smart contracts can autonomously track, regulate, and enforce compliance with sustainability standards and regulatory policies, ensuring that corrective actions are applied when necessary [127].

6.3. Challenges to the Applicability of the Cybersystemic Security Kit

This section extends the discussion in Section 4.4 by offering more reflection on the practical viability of the technologies that compose our proposed *Cybersistemic Security Kit*. These include smart contracts, oracles, ZKPs, SSI, and BC tokens. While each of these components shows great promise individually, their combined effectiveness—especially in supporting human–machine sustainability—requires critical examination.

To better synthesize the discussed BC-related technologies and their implications, Table 5 provides a comparative overview of their primary applications, strengths, and persistent challenges. This highlights the interplay between technological potential and implementation complexity in hybrid human–machine ecosystems.

As summarized in Table 5, while each BC-enabling technology contributes distinct value—such as traceability, privacy, trust, and decentralization—they also introduce notable technical, legal, and ethical challenges. Addressing these issues will require cross-disciplinary strategies, hybrid architectures, and a continued emphasis on transparency and human-centric design principles. Due to the possibilities and obstacles of the BC framework in its current state, it can be concluded that there are many opportunities for a *Cybersistemic Security Kit* to be part of the HBMSE proposed by our methodology. But more value still needs to be extracted from the perfect balance of the technologies involved.

Some variants could affect the BC framework. The main feature that is desired is the trustability of the transactions. This is achieved mainly by the essential decentralization that is provided by the Blockchain. However, the use of BC and thus the mix of the *Cybersistemic Security Kit* can be modulated, extended, or reduced case by case. For example, for the technologies related to ZKP, alternatives are available outside the mainstream BC framework in which they are more often found [120]. In addition, in the use case described in Section 5.1, the data model is essentially that of a centralized database, where the BC framework covers a complementary though fundamental role to data access, transmission, and runtime verification, when the application is seen as a whole [10].

The use of the methodology is designed to extract the best value from these possibilities, relying on a systemic process geared toward better harmonizing the role of humans and machines for overall sustainability.

Table 5. Overview of BC-related technologies and their role in industrial ecosystems.

Technology	Strengths and Applications	Challenges and Open Issues
Blockchain	Enhances traceability, security, and sustainability; supports automation in hazardous contexts [116]	Scalability, energy use, legal uncertainty, technical complexity, interoperability gaps
Smart Contracts	Used in supply chains and healthcare; enables automation [88]	Limited processing, post-deployment inflexibility, verification gaps [89,91–93]
AI + Smart Contracts	Helps mitigate smart contract vulnerabilities [95]	Explainability and transparency concerns [4,94,96]
Oracles	Bridge on-chain and off-chain data; key for BC applications [12]; trusted schemes, reputation protocols, distributed models [14,16,17,20,130]	Data manipulation, re-centralization, IoT complexity [11,13,15,18,19], lack of integrated HyR system frameworks despite AI support [21]
ZKP	Verifies data integrity without revealing it; used in supply chains and collectives [10,85]; recursive aggregation, hybrid models, AI integration [86,98,100]	Computation cost, trusted setup vulnerabilities, oracle integration difficulty [97,99], performance bottlenecks, lack of explainability [101]
SSI	Empowers agent-controlled credentials, aligns with ethical AI [102], GDPR-compliance, AI explainability, ZKP-enabled access control [51,103,105,106]	Scalability, integration, interdisciplinary gaps [87,104]
Blockchain Tokens	Used for flexible, ethical incentives; supports traceability [107]	Regulatory and technical feasibility for fractional NFTs [108,109]
Soulbound Tokens (SBTs)	Decentralized identity, ethical AI, privacy with structure rejection [110–113]	Smart contract complexity to preserve privacy and immutability at the same time

6.4. A Unifying Layer for Methodological Pluralism

SD modeling was used to explore centralized vs. decentralized supply chain control in [131], but the authors focused mainly on production efficiency. This work aims to extend the reach of SD by integrating it with cybernetics and sustainability dimensions for a more systemic framework.

It is not necessarily the case that our solution is a perfect solution. Each component can be substituted for a specific application. For example, SD could be replaced with advanced alternative solutions that study and synthesize the dynamics of systems. ABM, which is now included as a part of the proposed SD instance, could potentially itself handle the whole SD scope. This is also the case for other consolidated frameworks in the industrial playground like discrete-event dynamic systems, supervisory control theory, and reactive synthesis. However, in our experience in the industrial field, this is rarely the case outside of academic proposals: a one-size-fits-all solution has never worked, no matter how powerful the framework. This experience on the limits of solutions that do not follow methodological pluralism is supported in some valuable studies, such as [132].

Previous works [119,133] and developments within the ENOUGH project (Section 5.1) have addressed the limitations of siloed disciplines in system control and automation, advocating for a new Discrete-Event Simulation approach such as RMAS [119,133]. However, RMAS, holonic and ABM [45], and classical MBSE require integration within a higher-level framework. Here, SD offers a unifying design and decision-making layer, linking these approaches with the Law of Requisite Variety and supporting sustainability across HyR states.

Kruger et al. [132] discuss SD's role in embedding complexity theory into Operational Research, emphasizing its utility for modeling non-linear interactions and feedback loops. Similarly, Nugroho and Uehara [35] review SD, ABM, and hybrid models for social–ecological systems, noting that SD excels in feedback representation while ABM captures agent-level behavior. They call for enhanced hybridization and AI integration to improve model performance.

The integration of generative AI in SD modeling is growing. Veldhuis et al. [134] show that AI can synthesize simple CLDs and SFDs, while complex structures still need expert refinement—a limitation echoed in [4]. Meanwhile, Ghaffarzadegan et al. [29] explore generative agent-based models via LLMs, though not directly focused on SD constructs.

Abdelbari and Shafi [135] propose genetic programming and simulated annealing to generate SD models, including CLDs, SFDs, and equations, using input variables and structural constraints. These computational intelligence methods, combined with recent AI progress, reinforce SD's promise as a foundational framework for addressing complex HyR problems.

In light of both practical industrial experience and growing academic support, SD emerges not as a rigid prescription, but as a useful meta-framework capable of integrating diverse modeling approaches, aligning with complexity theory, and evolving through AI enhancements. This pluralistic adaptability is essential components in the proposed methodology for navigating the intricacies of HyR.

7. Conclusions

The research question that this work answers is the following: is it possible to establish a comprehensive cyber-systemic methodology that makes Hybrid Reality a controllable and sustainable phenomenon?

The answer is affirmative for what we have treated. We have provided a methodology that can be used to generate a solution to such a hard socio-technical problem.

This study highlighted the transformative potential of a Hybrid Reality framework, underpinned by Blockchain technology. By integrating concepts like cybernetics, System Dynamics, and Blockchain-driven innovations such as smart contracts, zero-knowledge proofs, and self-sovereign identities, the authors have proposed a methodology for fostering transparency, trust, and sustainable control of the interactions that arise in Hybrid Reality.

Of course, the solution proposed here for the interdisciplinary integration of various methods is subject to numerous variations and improvements. The intention was not to provide a definitive answer but to offer a path that, to the best of our knowledge, has never been attempted before.

The application of the proposed methodology is constituted by seven major steps:

1. Definition adoption. Adopt the definitions provided for Hybrid Reality in terms of the Agency–Environment state space. These definitions must be mapped onto the process under study. The process is viewed as a sequence of interactions between agencies and environments. The collection of these interactions defines the state space, and trajectories within this space form a trace that informs the workflow model of the Agency–Environment system.
2. Workflow execution. Execute the workflow derived from the mapped Agency–Environment interactions. This operational phase sets in motion subsequent methodological actions at pre-defined points.
3. Application of Ross Ashby's law. Apply Ross Ashby's law of requisite variety to interpret specific Agent–Environment interactions as cybernetic causal loops, establishing a unified framework for analysis.

4. System Dynamics modeling. Once the cybernetic interaction is defined, apply System Dynamics methods—such as Causal Loop Diagrams—to model the behavior of the system. Other tools like Stock and Flow Diagrams may also be employed depending on the complexity of the scenario.
5. Design of control elements. Use model-based systems engineering techniques to design the amplifiers and filters necessary to bring the Hybrid Reality cybernetic loop to equilibrium. This phase focuses on engineering the mechanisms required to manage system variety.
6. Technology-agency integration. Align the designed solutions with an appropriate mix of technologies and natural agencies. This step includes instantiating components from the *Cybersistemic Security Kit*—i.e., the available Blockchain technologies—to ensure secure and effective system implementation.
7. Recursive holonic design. Introduce holonic paradigms to recursively apply the methodology at deeper levels of granularity, if needed. At each level, a new Agency–Environment process can be defined and analyzed in the same structured way.

The ENOUGH project, funded by the EU under Horizon 2020, serves as both the motivation and initial testbed for validating the proposed methodology in the context of reducing greenhouse gas emissions in food supply chains. It offers a practical setting to apply all seven methodological steps. During the project, the need for a cyber-systemic approach to address emerging Hybrid Reality (HyR) dynamics became increasingly evident.

The nature of this paper is necessarily positional due to the ambition of the research pursued here. In fact, the research proposed here can be seen as the root of a tree of specific research, the branches of which will require validation and experimentation. However, the value of this perspective may lie in its potential to generate new strands of technical and scientific research guided by a renewed vision and approach—one that is particularly useful in controlling the technology-saturation effects observed in engineering disciplines when addressing socio-technical problems.

Nonetheless, we argue that only such an approach enables lateral thinking and opens pathways to otherwise intractable socio-technical and technological problems, typically constrained by rigid disciplinary boundaries.

The context in which the results of the research will have a primary impact is in the Green Deal of the European Union, which makes reference to the UN SDGs. The industrial target is the primary one in its multi-dimensional and multi-faceted sustainability impacts, but this study also reveals other potential societal areas of intervention.

Several barriers remain, primarily disciplinary ones. The key value of this position lies in promoting a top–down, integrative view of complexity, combining methods from both hard and soft sciences within a systemic and systematic framework—ensuring analyzability, transferability, and repeatability. Of course, any of the steps of the methodology presented in the example present their own technical difficulties and complexity. These difficulties are to be solved in the disciplines involved as problem parts contributing to a problem whole. The proposed methodology contains many components, such as Blockchain, System Dynamics, cybernetics, and generically Model-based Systems Engineering. Their relationship and interactions can be modified and modulated in many but systematic ways.

Finally, it is important to note that the propositions explored here only scratch the surface of the Hybrid Reality problem. Many variants and better methodology steps are surely possible and desirable. Here, the tentative aim has been to promote a small paradigm shift in the engineering and scientific community; we have aimed to promote this shift in a systematic way that is amenable to validation and verification of its effectiveness in real fields in the real world.

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Abbreviations

The following abbreviations are used in this manuscript:

AA	Artificial–Artifacts
ABM	agent-based modeling
AE	Agency–Environment
AI	artificial intelligence
AN	Artificial–Nature
BC	Blockchain
BPMN	Business Process Model and Notation
CLD	causal loop diagram
DCS	distributed control system
DFA	deterministic finite automaton
EU	European Union
GDPR	General Data Protection Regulation
FT	Fungible Token
GHG	greenhouse gases
HCA	holonic control architectures
HyR	Hybrid Reality
ICT	information and communication technologies
IoT	Internet of things
LLM	large language model
MBSE	model-based systems engineering
NA	Natural–Artifacts
NFA	non-deterministic finite automaton
NFT	Non-Fungible Token
NN	Natural–Nature
SBT	Soulbound Token
SD	System Dynamics
SDG	Sustainable Development Goal
SDS	Smart Data System
SFD	Stock and flow diagram
SSI	Self-sovereign identity
UN	United Nations
VSM	Viable System Model
ZKP	zero-knowledge proof
zk-SNARK	zero-knowledge succinct non-interactive arguments of knowledge
zk-STARK	zero-knowledge scalable transparent arguments of knowledge
XAI	explainable artificial intelligence

Appendix A. More on Automata

A friendlier, intuitive, and equivalent representation of the transition table in Figure 3 is provided to non-specialized readers.

In Figure A1, the NFA represented with the transition table in Figure 3 is rendered in the form of a graph. Note that only the first two rows of transitions have been rendered. This is a more common representation, and more intuitive, though for a limited number of states and edges. Here, it is shown to render a pictorial idea of the transition that happens. The transitions are indicated on the edges of the graph.

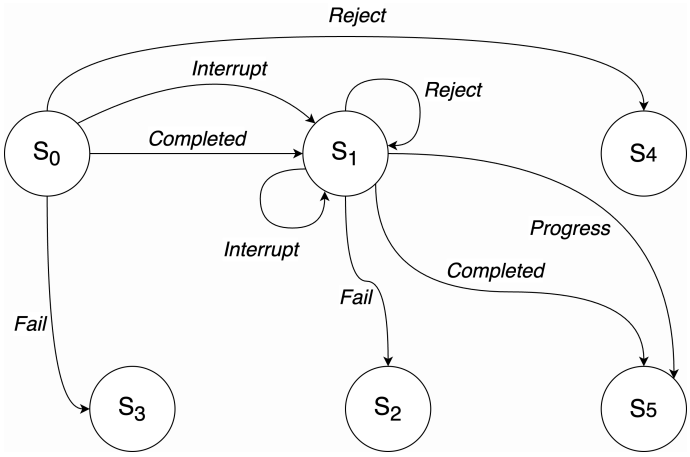


Figure A1. A state machine graph equivalent to the first two rows of the transition table of Figure 3.

Appendix B. Details of the CLD

In Table A1, details on the loops of Figure 6 are provided. By following the sequence of the variables in the table for each loop, the reader can figure out the corresponding path associated in the graph.

The B-type of loops are balancing effects, in which the stability of *S* lessens the need for more effort in the design of appropriate *F* and *G* systems to balance the HyR interaction. The R-type of loops are reinforcing. In this case, the reinforcement effect is due to less reliance on the safety and security introduced with the *Cybersystemic Security Kit* components. This means that the holonic and agent-based aspects have to be improved to catch up with the reduction in the sustainability of the interaction, necessarily raising the resulting varieties of *G* and *F*.

Measuring the involved variables is not straightforward. The CLD is not intended to provide precise quantitative dynamics. Transforming the CLD into a corresponding SFD (see, for example, [4]) is necessary to create a decision-making simulator, where some variables are refined and quantified. However, this is beyond the scope of this work.

Table A1. Details of the loops of the CLD in Figure 6.

Loop Tag	Description of Causality	Variables Involved in Loop [with Polarity]
B1	Stability of *S* reduces the demand for *G* and new designs associated with increasing the variety of *G*	*S* stability [−], *G* variety demand [+], HMBSE demand [+], Natural components [+], Holonic HyR interface variety [+], *G* variety [+]
B2	Stability of *S* reduces the demand for *G* and new designs associated with increasing the variety of F that matches and balances *G*	*S* stability [−], *G* variety demand [+], HMBSE demand [+], Natural components [+], Holonic HyR interface variety [+], *F* variety [+]
B3	Stability of *S* reduces the demand for *G* and new designs associated with increasing the variety of *G*	*S* stability [−], *G* variety demand [+], HMBSE demand [+], Artificial components [+], Holonic HyR interface variety [+], *G* variety [+]

Table A1. *Cont.*

Loop Tag	Description of Causality	Variables Involved in Loop [with Polarity]
B4	Stability of *S* reduces the demand for *G* and new designs associated with increasing the variety of *F* that matches and balances *G*	*S* stability [−], *G* variety demand [+], HMBSE demand [+], Artificial components [+], Holonic HyR interface variety [+], *F* variety [+]
B5	Stability of *S* reduces the demand for *F* and new designs associated with increasing the variety of *G* that matches and balances *F*	*S* stability [−], *F* variety demand [+], HMBSE demand [+], Natural components [+], Holonic HyR interface variety [+], *G* variety [+]
B6	Stability of *S* reduces the demand for *F* and new designs associated with increasing the variety of *F*	*S* stability [−], *F* variety demand [+], HMBSE demand [+], Natural components [+], Holonic HyR interface variety [+], *F* variety [+]
B7	Stability of *S* reduces the demand for *F* and new designs associated with increasing the variety of *G* that matches and balances *F*	*S* stability [−], *F* variety demand [+], HMBSE demand [+], Artificial components [+], Holonic HyR interface variety [+], *G* variety [+]
B8	Stability of *S* reduces the demand for *F* and new designs associated with increasing the variety of *F*	*S* stability [−], *F* variety demand [+], HMBSE demand [+], Artificial components [+], Holonic HyR interface variety [+], *F* variety [+]
R9	*S* stability reduces *G* demand and the need for new components and security, increasing reliance on the holonic interface, which raises *G* variety	*S* stability [−], *G* variety demand [+], HMBSE demand [+], Natural components [+], BC, ZKP, SSI components [−], Holonic HyR interface variety [+], *G* variety [+]
R10	*S* stability reduces *G* demand and the need for new components and security, increasing reliance on the holonic interface, which raises *F* variety	*S* stability [−], *G* variety demand [+], HMBSE demand [+], Natural components [+], BC, ZKP, SSI components [−], Holonic HyR interface variety [+], *F* variety [+]
R11	*S* stability reduces *G* demand and the need for new components and security, increasing reliance on the holonic interface, which raises *G* variety	*S* stability [−], *G* variety demand [+], HMBSE demand [+], Artificial components [+], BC, ZKP, SSI components [−], Holonic HyR interface variety [+], *G* variety [+]
R12	*S* stability reduces *G* demand and the need for new components and security, increasing reliance on the holonic interface, which raises *F* variety	*S* stability [−], *G* variety demand [+], HMBSE demand [+], Artificial components [+], BC, ZKP, SSI components [−], Holonic HyR interface variety [+], *F* variety [+]
R13	*S* stability reduces *F* demand and the need for new components and security, increasing reliance on the holonic interface, which raises *G* variety	*S* stability [−], *F* variety demand [+], HMBSE demand [+], Natural components [+], BC, ZKP, SSI components [−], Holonic HyR interface variety [+], *G* variety [+]
R14	*S* stability reduces *F* demand and the need for new components and security, increasing reliance on the holonic interface, which raises *F* variety	*S* stability [−], *F* variety demand [+], HMBSE demand [+], Natural components [+], BC, ZKP, SSI components [−], Holonic HyR interface variety [+], *F* variety [+]
R15	*S* stability reduces *F* demand and the need for new components and security, increasing reliance on the holonic interface, which raises *G* variety	*S* stability [−], *F* variety demand [+], HMBSE demand [+], Artificial components [+], BC, ZKP, SSI components [+], Holonic HyR interface variety [+], *G* variety [+]
R16	*S* stability reduces *F* demand and the need for new components and security, increasing reliance on the holonic interface, which raises *F* variety	*S* stability [−], *F* variety demand [+], HMBSE demand [+], Artificial components [+], BC, ZKP, SSI components [+], Holonic HyR interface variety [+], *F* variety [+]

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