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Review

Artificial Intelligence for Sustainable Complex Socio-Technical-Economic Ecosystems

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Abstract: The strong and functional couplings among ecological, economic, social, and technological processes explain the complexification of human-made systems, and phenomena such as globalization, climate change, the increased urbanization and inequality of human societies, the power of information, and the COVID-19 syndemic. Among complexification's features are non-decomposability, asynchronous behavior, components with many degrees of freedom, increased likelihood of catastrophic events, irreversibility, nonlinear phase spaces with immense combinatorial sizes, and the impossibility of long-term, detailed prediction. Sustainability for complex systems implies enough efficiency to explore and exploit their dynamic phase spaces and enough flexibility to coevolve with their environments. This, in turn, means solving intractable nonlinear semi-structured dynamic multi-objective optimization problems, with conflicting, incommensurable, non-cooperative objectives and purposes, under dynamic uncertainty, restricted access to materials, energy, and information, and a given time horizon. Given the high-stakes; the need for effective, efficient, diverse solutions; their local and global, and present and future effects; and their unforeseen short-, medium-, and long-term impacts; achieving sustainable complex systems implies the need for Sustainability-designed Universal Intelligent Agents (SUIAs). The proposed philosophical and technological SUIAs will be heuristic devices for harnessing the strong functional coupling between human, artificial, and nonhuman biological intelligence in a non-zero-sum game to achieve sustainability.

Keywords: artificial and biological intelligence; complex coevolutionary systems engineering; sustainability; multi-objective optimization; sustainable universal intelligent agents

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1. Introduction

> " ... For the world of our own making has become so complicated that we must turn to the world of the born to understand how to manage it. That is, the more mechanical we make our fabricated environment, the more biological it will eventually have to be if it is to work at all. Our future is technological; but it will not be a world of grey steel. Rather our technological future is headed toward a neo-biological civilization ... " [1].

The concept of sustainability is increasingly considered a "non-negotiable imperative" [2], and, as such, it has become an almost essential component of discourses designed to support and justify decision-making at all levels of human activities. Usually, the concept's definition is taken from a paragraph by the World Commission on Environment and Development [3]: " ... meet the needs and aspirations of the present without compromising the ability to meet those of the future ... " While such a definition has served as a basis for discussion, it is an ambiguous section, from a paragraph, inside a three-hundred-page book, describing a lot more than what is assumed as a consensus: the multi-dimensional importance, in space and time, of achieving sustainability for human-made systems, and for the Biosphere from which humanity's existence depends. Furthermore, the fact that what must become sustainable are complex socio-technical-economic ecosystems, with their essentially nonlinear dynamical nature, has not been explicitly acknowledged. Here, we discuss the need for integrating artificial and biological intelligence within the framework of a complex coevolutionary systems engineering approach for the achievement of sustainable human-made complex socio-technical-economic ecosystems.

2. The Technological Anthropocene

Scientists define the current geological period as the Anthropocene [4], due to both humanity's relative success as a species, and its powerful impact on the planet. A factor that strongly explains the success and impact of human societies is technology, which has been described as humanity's "extended cognitive systems" for problem-solving purposes [5–8]. Ideally, human biology, intelligence, technology, and culture, coevolve [8,9], enhancing human capabilities to, in turn, coevolve with ecological environments [8–10].

Technological tools have enabled human societies to reach a population size of more than 7.9 billion by April 2022 [11], with associated increments in the human appropriation of the earth's ecological processes, such as the net primary production (up to 44 % of the planet's total by 2050), and the resulting negative impact on the Biosphere [12]. Other consequences of the Anthropocene are soil degradation, pollution, climate change, and massive extinctions, with more than 37,400 biological species currently known to be in danger [13–15]. All of the above is translated as a reduction in the Biosphere's capacity for sustaining her metabolic processes, and consequently, for producing ecosystem services on which the survival of the human species depends. Technology plays an essential role in The World Economic Forum's [16] lists of most likely (and having the greatest impact globally) "critical threats to the world". Among these threats are: infectious diseases, livelihood crises, extreme weather, climate action failure, cyberattacks, bursting of asset bubbles, biodiversity loss, human-made environmental disasters, adverse tech advances, cyberterrorism, digital power concentration and inequality, economic fragility, livelihood crises, unemployment, societal divisions, erosion of social cohesion, and youth disillusionment, resulting in, for example, tribalism, involuntary migration, xenophobia, and protests against inequality.

As evidence of the destructive impacts of the Anthropocene on the Biosphere accumulates, it has been suggested that the ecosystems could do better without humans, implying erroneously that:

(i) past ecosystems' dynamics were somehow "better" than those during the Anthropocene;
(ii) that humans are not part of "Nature"; and
(iii) that change can be stopped or reversed, ignoring the evolutionary nonlinear dynamics of the Biosphere, where the change (including extinction and biological novelty) is essential for the sustainability of life on the planet [13].

However, what cannot be denied is that human societies cannot exist without the Biosphere, since, apart from its essential reliance on the ecosystems, the human species is a component of the Biosphere.

Despite regional increases in biodiversity [13], and in the efficiency of, for instance, food production [12], there have been anthropogenic phenomena such as the increased frequency of extreme meteorological events (e.g. droughts, heatwaves, cyclones), involuntary human migrations, and catastrophes such as the unprecedented intensity and extent of the 2019–2020′s bushfires in Australia (with dozens of human deaths, the loss of thousands of homes, livelihoods and buildings, more than 10 million burned hectares, and 1.25 billion dead animals) [17]. Most importantly, the current global COVID-19 syndemic (spatiotemporal clusters of health-related issues and their future consequences, emerging from nonlinear interactions between diseases and social/biophysical/economic factors) [18,19], and its present and future massive consequences for human livelihoods, make imperative the need to achieve sustainable human societies, acting against the roots and impact of the anthropogenic damage to the Biosphere.

3. Complexification

The increasingly faster pace of ecological, economic, social, and technological coevolutionary processes and interdependencies (lowering or eliminating barriers against interactions among ecosystems, people, business, institutions, and governments), helps to understand the emergence of complex phenomena. Examples of the latter are globalization, economic, political, and ideological crises, pandemics, technological revolutions, criminal and terrorism webs, climate change and its consequences, mass extinctions, greater urbanization, wealth and inequality of human societies, and the power of information, misinformation, and knowledge, all of which imply both new challenges and opportunities.

From an engineering perspective, the complexity of any given system depends on the number of its components, feedbacks, decisions, objectives and purposes, individuals, organizations, categories, and hierarchies (e.g., systems, subsystems, metasystems, and components.), where the greater the number, the more complex the system. Other considerations refer to the degree of conflict and incommensurability concerning, among systems' purposes and objectives, the strength of the coupling between the system's components, and between the system and its environment [20], and to the introduction of completely new, both known and unknown, variables [21] at multiple spatiotemporal scales and hierarchies.

Deep changes within the dynamics of any given nonlinear open system are also due to nonlinear changes in its environment. A complex system's behavior emerges from its interdependency with its environment, and functional couplings among its own and the semi-independent components that it shares with other systems. From complex systems' nonlinear dynamics also emerge known and unknown secondary effects that can propagate without control outside the system's boundaries [22]. Another consequence is that systems, their problems, their environments, and their phase spaces (dynamic, intractable multidimensional sets of all possible states for a given real-world complex system) [23] coevolve, with the consequent quantitative and qualitative changes in the system's dynamics [20].

The complexification of a given dynamical system is observed as epiphenomena, described as non-anticipated, hard to understand behaviors emerging from nonlinear dynamics, observed at a higher hierarchical level than that of the variables from which they emerge, and that cannot be explained as linear (proportional) causal effects from the behavior, at a lower hierarchical level, of the system's components [24–26]. Further features of complexification are [20,27–33]:

- incomplete knowledge, uncertainty, and unpredictability;
- asynchronicity (the value of a given state variable is not updated simultaneously in response to changes in auxiliary or control variables, which results in changes that apparently do not follow their "cause");
- greater difficulty in understanding, explaining, and controlling present and future events; and
- a greater need for information to expand and maintain the system's dynamic phase space, to meet challenges such as high performance, security, and extreme environmental conditions, and, of course, to achieve sustainable outcomes.

The complex systems' increasingly greater need for information should also be considered in terms of the social, technological, economic, ecologic, and thermodynamic costs of acquiring, generating, processing, understanding, updating, evaluating, applying, and managing such information.

Figure 1 shows some of the aforementioned variables and their nonlinear dynamics [34]. The semicircular, bidirectional arrows represent the strong, coevolutionary functional couplings among the state variables, where each of the latter influences, and is influenced by, other variables and by the whole system's dynamics. Among the outcomes of such dynamics are the need for complex systems approaches, and for ad hoc theoretical, mathematical, engineering, and computational tools and heuristics for describing, understanding, harnessing, and modifying those nonlinear dynamics [20,35].

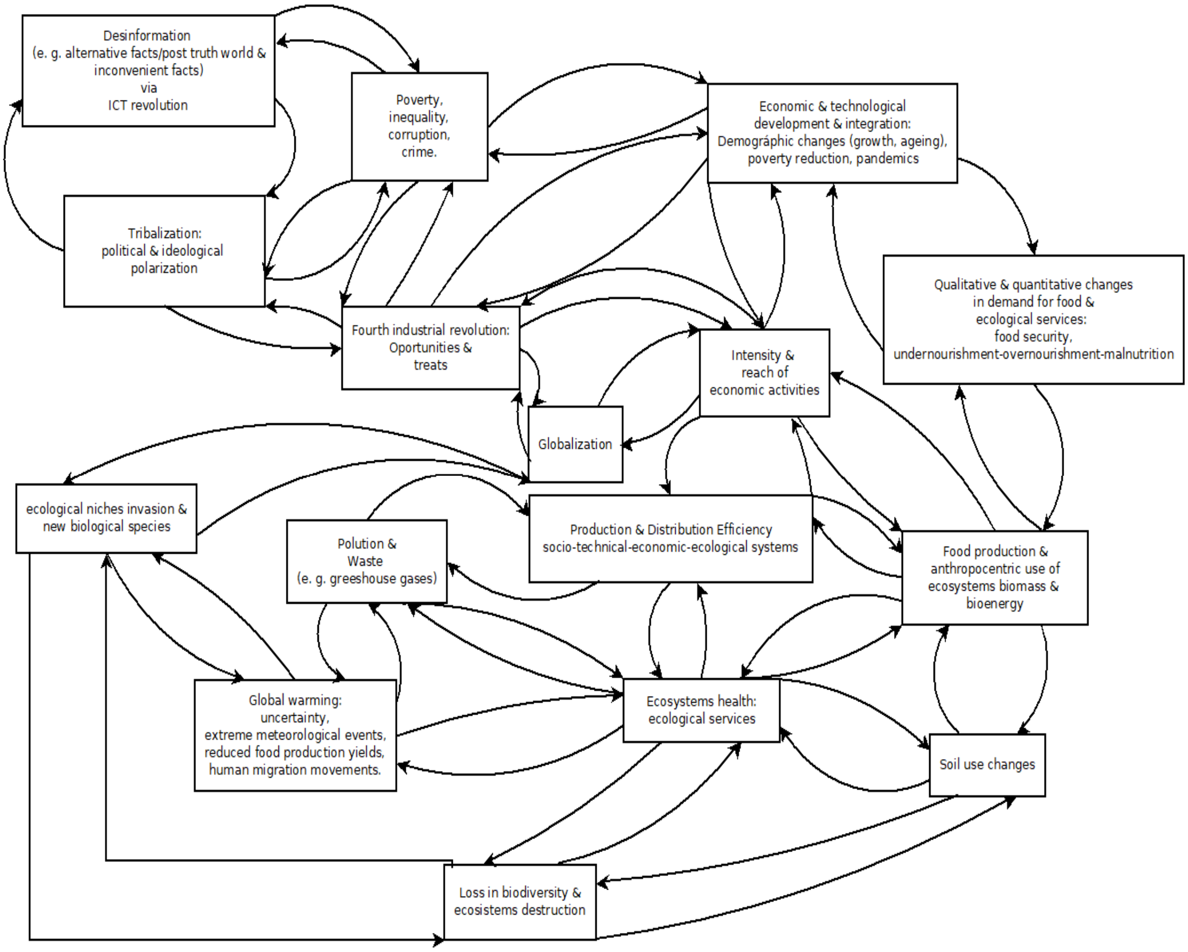

Figure 1. Some of the state variables and functional couplings related to sustainable human-made complex systems.

Nonlinear coevolutionary processes such as those illustrated in Figure 1 help to understand the complexification of human-made systems [36], with the latter emerging from the nonlinear functional couplings between social, technological, and economic ecosystems, from which humanity's complex socio-technical-economic ecosystems emerge.

4. The UNO's Agenda for Sustainable Development

In 2015, the General Assembly of the United Nations Organization (UNO) adopted the Agenda for Sustainable Development as a blueprint for eliminating extreme poverty while restoring and securing the planet, with the active participation of all member countries and stakeholders as the sinequa-non requirement for achieving the Agenda's purposes. The Agenda contains a set of seventeen Sustainable Development Goals (SDGs), which, in turn, are composed of one hundred and sixty-nine targets, to be achieved and evaluated by the year 2030 [37].

Although the final version of the Agenda described its goals and targets as " . . . integrated and indivisible . . . " [37], it has been criticized because of a " . . . weak, fragmented and intermittent . . . " scientific input, an overly large and "unpractical" number of goals and targets, and biophysical targets that were " . . . vague . . . and lacked detailed quantification . . . ", and for ignoring the need for a " . . . strong . . . " integration of such goals and targets to solve potential conflicts and trade-offs [38–41]. Furthermore, the Agenda needs a larger input from the scientific research community working on complexity sciences, artificial intelligence, management science, systems engineering, and operations research, despite earlier works advising about the link between sustainability and the complexity-generating interactions from which human-made systems emerge (e.g., [42–46]).

Among the missing issues in dealing with the Agenda's design and implementation is the explicit recognition of the functional coupling [34] of ecosystems and human-made systems, emerging from the strong, dynamic nonlinear spatial and temporal interdependencies among systems, subsystems, and meta-systems, resulting in complex socio-technical-economic ecosystems, which, we suggest, are the Agenda's objects of interest. Emerging from functional couplings are the following missing issues:

- the dynamic epiphenomena of complex socio-technical-economic ecosystems' behavior, which is defined by and defines the dynamic identity, in time and space, of such systems [20,25,30,31,47–51];
- non-decomposability (parts of the system cannot be investigated separately from the rest, effectively preventing simplifications);
- asynchronous behavior;
- components (agents) that can respond differently to the same stimuli;
- increased likelihood of catastrophic, abrupt, large qualitative changes in the systems' behavior;
- irreversibility due to thermodynamics-quantum mechanics, and to the systems' sensitivity to initial conditions;
- difficulty in understanding and controlling complex systems' behavior,
- the impossibility of long-term, detailed predictions,
- problems, systems, environments, and intractable phase spaces coevolve dynamically, meaning that each time a solution is found and implemented, the question changes, thus needing a new, different set of solutions;
- sustainability goals and targets are dynamic, nonlinear, constrained in time and space, semi-structured, frequently incommensurable, and mostly non-cooperative or in conflict, dealing with risks, uncertainty (unforeseeable changes for which no subjective quantification is possible), incomplete knowledge, multiple shareholders and stakeholders, high stakes, and " … the urgent need to act … " [20,37,40,51,52];
- the acknowledgment of regional increments on the number of biological species, ecosystems' net primary production, and improved human resource use efficiency, due to advances in science and technology [12,13,53–56], which do not necessarily compensate for the losses;
- the need to change human perceptions, beliefs, and attitudes towards the Biosphere, from the false dichotomy of ecological versus human-systems sustainability (e.g., [57]) to the fact that the human species is an indivisible component of "Nature", whereby achieving sustainable outcomes essentially means the enhancement of the coevolutionary capacities of both human-made systems and the Biosphere;
- the fact that nonlinear change is not only unavoidable, but the essence of Nature's complex systems, which are sustainable if they can preserve their capacity to coevolve with their dynamic environment [20];
- for complex socio-technical-economic ecosystems, sustainability is an epiphenomenon emerging from non-linear coevolutionary functional couplings [58] among their components and between such complex systems and their environments. Hence, the success or failure of achieving sustainability depends on coevolutionary functional couplings.

A quintessential example of the kind of complex challenges of achieving the Agenda's goals and targets arises from the nonlinear dynamics of one of the main focuses of the UNO's Agenda: extreme poverty reduction.

The World Resources Institute [59] projects that 9.8 billion humans will be living on the planet by the year 2050. Among the Agenda's targets is the reduction in the world's population remaining in extreme poverty, from 36% in 1990 [60] to 3% by 2030. By 2015, there was a reduction of more than 1.1 billion people living in extreme poverty, to 10% of the total human population [60]. By 2018, more than half the world's population was considered middle class or rich [61], and only 9% of the human population was living in low-income countries [62]. However, the gains achieved in poverty reduction in the last quarter of a century have been severely affected by the COVID-19 syndemic (the pandemic, associated economic crises, socioeconomic inequalities, plus armed and social conflicts, and climate change). The World Bank calculates that between 88 and 115 million people worldwide regressed to extreme poverty in 2020, with the likely future addition of 110 to 150 million, for a total of up to 729 million people living in extreme poverty by the end of 2021 [63].

Poverty reduction contributed to the achievement of other of the Agenda's targets, such as higher labor productivity, greater mental capacity, and longer, healthier lives, which, in turn, resulted in nonlinear increments in the human population's size and income [37,64,65]. Other outcomes are nonlinear increments in the demand and quality for socio-economic services (e.g., energy), for goods such as nutrient-rich energy-dense food (e.g., consumption of animal-based foods is projected to increase by 2030 by between 66% and 170%, depending on the product, compared to the year 2000 figures), and for ecological services [59,65–67]. In turn, these outcomes increase the pressure (i.e., greater human appropriation of net primary production, water scarcity, and variability, floods and droughts, soil use changes, pollution, biodiversity loss, greenhouse gasses, etc.) on the Biosphere's capacity for fulfilling humanity's needs [12,39,59,68,69]. Other emergent outcomes are nonlinear changes in demand-supply and costs–prices of goods and services, human health hazards (e.g., undernutrition–overnutrition, diseases, zoonosis, and anthroponosis), and the production and management of waste [39,59,65,70–73].

Although the whole of humanity suffers as a consequence of a degraded Biosphere, the most affected are the poorer, with impacts on other of the Agenda's goals, such as hunger elimination, reduction in child mortality, and the fight against diseases [44]. Paradoxically, the nonlinear dynamics described above have also resulted in the promotion of qualitative cultural changes among human societies, such as increased social awareness of the importance and meaning of ecosystems for human well-being (e.g. [69,74–77]), and the awareness of the impact of inequality among human societies [78] (Figure 2).

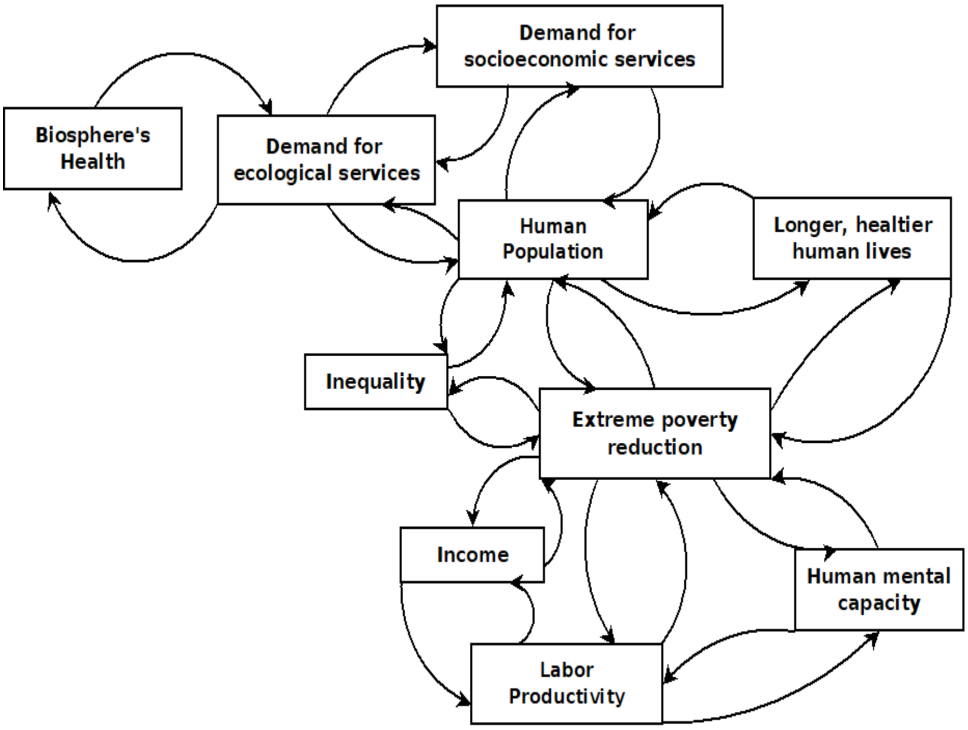

Figure 2. Nonlinear dynamics of extreme poverty reduction.

The overwhelming complexity described simplistically with the two figures above underlines the fact that the achievement of the all-interdependent goals and targets for sustainable human societies implies dealing with the nonlinear dynamics of complex systems, and, as such, the obvious need for complexity and the contributions of systems engineering sciences to achieving sustainable complex socio-technical-economic ecosystems.

5. Engineering Complex Systems

If one considers:

(i) the high-stakes;
(ii) the nonlinear dynamics and associated unpredictability, uncertainty, and their semi-structured, intractable, and incommensurable essence;
(iii) time, biological, technological, sociocultural, economic, ecological, and thermodynamical constraints;
(iv) multiple stakeholders, shareholders, and spatiotemporal dimensions; and
(v) the urgent need for feasible, effective, efficient solutions, and their unforeseen short, medium, and long-term impacts,

Then, achieving sustainable complex coevolutionary socio-technical-economic ecosystems is indeed a formidable and nonnegotiable complex challenge.

To deal with such a challenge, a review of the lessons learned from successful high-stakes, complex large-scale engineering projects is useful. An example comes from the National Aeronautics and Space Agency (NASA), with the concepts of systems management and systems engineering, for the holistic integration of social with "hard" sciences [79]. Systems management emphasizes sociocultural and managerial solutions to large-scale, complex, novel, and heterogeneous technical issues [80]. In turn, system engineering integrates, via tradeoffs and compromises, multiple purposes and objectives, and Science, Technology, Engineering, Mathematical, and Medical (STEMM) disciplines, " … to produce a coherent whole … ", identify, develop, implement, integrate, and evaluate human cooperation and technology for the achievement, within imposed constraints, of large-scale complex projects [79]. Both systems management and engineering integrate technological research and design with managerial abilities to ensure the success and reliability of large-scale complex projects under financial, time, technological, and social constraints [80]. Whatever the limitations and contextual restrictions of systems management and engineering, and NASA's anecdotal successes and failures, the experience acquired from their implementation should be considered for the achievement of sustainability outcomes.

6. Sustainability as a Multi-Objective Optimization Problem

At the intersection of engineering, sustainability, and complexity sciences, sustainable, complex, coevolutionary socio-technical-economic ecosystems exhibit enough efficiency to exploit their dynamic phase space and enough flexibility to explore and coevolve with their environments [46]. Efficiency refers to the aptitude of a system for achieving multiple, dynamic, constrained, and mostly incommensurable and conflicting objectives and purposes while performing below threshold values for failure. In turn, flexibility refers to a system's dynamic capacity to coevolve with its changing biophysical and socio-economic environment for a given time horizon, via the generation of high quality, diverse, and feasible optimal sets of solutions, to face uncertainty [20].

Sustainability engineering problems are partially "hard" because their solution requires precise data and calculations. This characteristic makes the problems "structured", meaning that the initial situation, the objectives, and the tools for solving these problems are well-defined and quantifiable, with standard, technically optimal solutions generally found via numerical methods [81,82]. Sustainability engineering problems also encompass unstructured processes, which are not well-defined situations without ready-made solutions, and where human intuition and values (i.e., purposes, beliefs, happiness, self-fulfillment, well-being, etc.) are essential [82,83]. Hence, sustainability engineering problems are semi-structured, implying a combination of both numerical procedures and intuitive, subjective judgment, and the need for deep and holistic approaches [20].

Solving sustainability engineering problems means the achievement of multiple, dynamic, conflicting biophysical and socioeconomic optimization objectives and subjective purposes, under dynamic uncertainty, and restricted access to materials, energy, and information, and within a given time horizon [20,84–87]. The objectives are at least partly incompatible or incommensurable, and non-cooperative or conflicting (at some stage, one objective cannot be improved without reducing the value of another) [46,88].

From an engineering perspective, achieving sustainability for complex systems means solving sets of non-linear, hard, semi-structured, constrained, dynamic, difficult multi-objective optimization problems, with conflicting objectives and subjective purposes, and intractable phase spaces [46]. To solve such problems, one should start by defining the phase space where the human species can live, for as long as possible, in a coevolutionary dynamic equilibrium with the ecosystems from which the species depends. This implies, among other factors, achieving acceptable standards of well-being and equity for all human individuals [77,89], while preserving a phase space as large and diverse as possible to coevolve with a healthy Biosphere.

In turn, the above implies the generation of sets of tradeoffs, non-dominated optimal solutions, obtained from multidimensional objective and decision variables' phase spaces since, for optimization problems with more than one conflicting objective, there is no single optimal solution [90,91]. Such a non-dominated set of solutions can be considered to be an optimal option to solve the optimization problem, from which human decision-makers, with higher-level information (i.e., non-structured information such as preferences, attitudes, beliefs, ethical norms, etc.), classify, choose, and assume responsibility for the implemented solutions [20].

Because of their non-linear combinatorial essence, and the size of their dynamic phase space, sustainability problems are also difficult, computationally hard, or intractable (no polynomial-time algorithm exists to solve this kind of problem), meaning that exploring the full combinatorial size of the decision variables' phase space to solve them exactly (e.g., finding the global optimum) would require unpractically large amounts of computational power and time, and/or that global optimal solutions may not exist at all [92–94]. Hence, the non-dominated optimal solutions for intractable multi-objective sustainability problems are not demonstrably globally optimal, but only good-enough, superior, locally optimal, or efficient [95,96]. In any case, any optimal solution, being local or global, is temporary, due to the dynamic nature of complex systems' phase space.

Axelrod and Cohen [97] proposed that a suitable approach for solving complex problems of the kind described above comes from a subfield of artificial intelligence, i.e., evolutionary computation, which emerges at the intersection of evolutionary biology, social design, and computer sciences. As an example of evolutionary computation procedures, multi-objective evolutionary algorithms (MOEAs) are population-based computational simulations of biological evolution [91], that harness the intrinsic complexity of the systems of interest to formulate and solve intractable, nonlinear multi-objective engineering optimization problems.

MOEAs balance intensification (the exploitation of the accumulated search experience) and diversification (the exploration of the phase space), applying genetic operators such as crossover (recombination), mutation, and selection, to generate populations (sets) of fit (high quality), diverse solutions (the nondominated, efficient, locally optimal Pareto set) as quickly as possible. These metaheuristic tools search for and generate multiple solutions in parallel, without needing supplementary information on the problem, apart from the objective functions' target qualitative values (e.g., maximization, minimization) [91,98]. MOEAs are flexible, adaptable, robust, effective, efficient, highly non-linear, massively multifaceted, stochastic, complex, and able to deal with features such as discontinuities, multi-modality, disjoint feasible spaces, and noisy function evaluations. MOEAs can exploit different fitness functions simultaneously, performing multiple direct parallel searches that generally result in an increase in the fitness of solutions from one generation to the next; and are among the few and most useful tools for solving real-world intractable nonlinear multi-objective problems [90,91,94,99–102].

7. Universal Intelligence for Sustainability

Among the emergent technologies of the last one hundred years, the field of artificial intelligence (AI) has been a powerful tool for the development and well-being of human societies, contributing to advances in domains such as healthcare, transportation, formal and informal education, scientific discoveries, manufacturing, agricultural production, weather forecasting, public safety and security, entertainment, and defense [103,104]. PricewaterhouseCoopers [105] projected that the global Gross Domestic Product (GDP) will be 14% higher (USD 15.7 trillion) in 2030 due to the implementation of AI. Unsurprisingly, the field of AI is considered a top research and development strategy for national governments around the world (e.g., [106]).

AI can be described as the field devoted to " … making machines intelligent, and intelligence is that quality that enables an entity to function appropriately and with foresight in its environment … " [107]. Depending on the kind of problems the tool is designed to solve, AI can be subdivided into general-purpose (strong), and narrow AI. Narrow AI is supposedly based on intelligent biological behavior to solve specific complex problems [108]. Among narrow AI tools are in-field sensor networks, computer vision, data mining, robotics, and machine learning [109]. A subfield of narrow AI is "nature-inspired computing" [110], comprising tools and techniques for optimization purposes based on biological and physical processes, such as evolutionary algorithms [91].

In turn, general-purpose, strong, or human-level AI [111] refers to the achievement of thinking and consciousness by a computer, making it capable of solving general complex problems [108,112]. Hence, general-purpose AI's implicit goal is biological intelligence replacement (including that of humans) [113].

Although the development of the field of AI is robust, as with every human endeavor, it is not exempted from challenges and controversies. These include the application of AI to the development of semi-autonomous lethal weapons, the social and societal risk of diminishing personal interactions due to the use of AI, the jobs lost to AI and other cyber-biophysical technologies, and the associated deeper wage gap between, on one side, the less-educated, and on the other, the highly trained workers of information and communication technologies [104,114–116]. The latter can be associated with the likelihood of increasing socio-economic inequality [103,116], and even the risk of irrelevancy for non-qualified human workers [89]. Another fear refers to the controversial scenario of the complete substitution of the human species for a super-intelligent version of strong AI [117] since strong AI is conceptualized as a "better" replacement for the supposedly limiting components of complex systems: humans [118].

While the achievement of strong AI is a matter to be solved in the future [111], the fact that the technology has not been able, so far, to reproduce human-like intelligence and consciousness is, at least partially, due to big differences between AI and biological intelligence.

AI, as a product of biological intelligence, is a technological tool based on data and the information-processing power of discrete machines that carry out a series of interdependent operations to generate and store discrete data and information, using discrete, finite, and closed algorithms. Although there has been some interest in developing AI computational hardware and software inspired by biological intelligence, such forms of computation do not result from an in-depth understanding of the biological structures and processes from which biological intelligence emerges, since such understanding is at best metaphorical and incomplete [113,119–121]. There is also AI's need for very large amounts of both human-generated data and information (sample complexity, [122]), and of computer processing power and its associated economic and thermodynamic costs (e.g., [123]) to, for instance, train artificial neural networks (ANN) to execute narrow AI tasks (e.g., playing and winning games). Furthermore, there are the issues of transitive inference, meaning that AI tools have restricted capacity to make logical inferences, such as the application of prior contextual real-world knowledge to solve real-world problems [119,124,125]; the challenges associated with the integration of different kinds of data and methods from different sources; the value alignment problem [126] in dealing with non-structured issues such as those related to, for instance, the subjective side of the concept of well-being; and of catastrophic forgetting, referring to the inability of AI (e.g. ANNs) to learn multiple tasks sequentially (continuous learning) [127].

In turn, biological intelligence emerges from at least 4.2 billion years of life's coevolutionary processes on Earth, and as such, is an epiphenomenon that enables an individual or a species to coevolve with its environment. Biological intelligence can be described as " . . . the ability to (flexibly) solve problems using (information and) cognition rather than instinct or trial and error learning" [128,129]. Such a definition distinguishes between instinctive and intelligent behaviors. Instinctive behaviors appear to be intelligent, but are the outcome of evolutionary mechanisms designed for specific situations, and thus cannot be applied outside their evolutionary context (e.g., the dance of bees to communicate the location of nectar) [128].

Biological intelligence refers to the set of evolutionary behaviors that can be flexibly applied to completely new contexts, where such behaviors are the outcome of cognition, flexible thinking, inferential reasoning, imagination, insight, foresight, consciousness, etc. [128,129]. Biological intelligence emerges not only from not-well-understood open nonlinear processes among cells, tissues, structures, properties, and functions of physiological systems but also from coevolutionary interactions of systems and subsystems (e.g., individuals and societies) with their contextual biological and abiotic environments. Furthermore, biological intelligence also emerges from the coevolutionary interdependence between instinctual and intelligent behaviors and is defined by any given biological organism's needs, allowing biological beings to continuously learn to master and modify the things they need to survive [121].

Biological intelligence is described and expressed on senses, reflexes, learning, intuition, cognition, and consciousness, and its biological, physiological, psychological-ethological, cultural, technological, and socio-ecological plasticity, relying on the functional dynamic, variable, open-ended, and diverse architecture of brains, nervous systems, organisms, and their coevolutionary cognitive environments, with no internal computations, representations, or algorithms [120]. For biological intelligence, niche-constructed structures (including ecosystems, culture, and technology) function as extended coevolutionary cognition tools ("extended cognitive systems") [7,8,129], which greatly enhance biological intelligence capabilities to solve complex survival problems. Hence, biological intelligence is embodied, emerging from coevolutionary interactions with its environment, which, along with path dependence, and the diverse evolutionary structures and processes of biological organisms and species' perceptions, makes each intelligent individual, experience, and species, contextual and unique [32,121,129–131]. As an example of biological intelligence, human intelligence must be assessed in terms of its contribution to the survival of the species [121,129].

Although the general AI goal is to mimic biological intelligence, a great deal of AI projects imitate processes of biological instinctive (not intelligent) behaviors. The last main differences between artificial and biological intelligence highlighted here refer to the way biological organisms use prior knowledge and experiences to deal with novel situations, and the efficiency of biological intelligence to deal with complexity and uncertainty by inferring future states from very little data and information, via data-compressing and error-correcting fitness procedures [119,121,124,125,132], and by the genetic, phenotypic, and functional variability of the biological coevolutionary responses to the environment.

Biological and artificial intelligence work best when conceptualized as complementary, since most of the limitations associated with the development and application of AI disappear when coupled with biological intelligence. Furthermore, it can be argued that the purpose of AI is to reduce the limitations of human intelligence. Cases where both kinds of intelligence bind with each other (e.g., the concept of “the centaur”, where humans and machines complement each other to perform above the levels attained by each group alone) are among the most successful types of technological development [118]. Among the approaches to achieve such integration are Daugherty and Wilson’s [133] “fusion skills” concept, where narrow AI interacts with, amplifies, and is embodied to its human users to provide them with “superhuman capabilities” for solving complex problems; and Johnson and Vera’s [118] “teaming intelligence”, described as the integration of people and AI via the application of knowledge, skills, and strategies for understanding, supporting, and harnessing the interdependence among humans and their technology. Given the high stakes, urgent need, and complexity of achieving sustainable complex socio-technical-economic ecosystems, there is the need for the synergetic outcome emerging from pairing biological intelligence and artificial intelligence (AI) to face such a complex challenge.

Although this paper has discussed a Nature-inspired operational definition of sustainable complex systems, it is worth trying to elucidate what has been Nature’s answer to the sustainability problem. The only known example of truly sustainable complex systems is the Biosphere, which, as the outcome of coevolutionary processes, is Nature’s engineering solution to the riddle of the emergence and preservation of life on Earth for at least 4.2 billion years (from which the human species has been around only approximately 300,000 yrs.), via their dynamic efficiency and open-ended flexibility.

Here, we suggest that sustainability for complex socio-technical-economic-ecosystems can be achieved by harnessing Nature’s “engineering power” via the recognition of the nonlinear dynamic functional coupling between the human species and the rest of the Earth’s Biosphere, expanding and applying the “fusion skills” [133] and “teaming intelligence” [118] concepts. Furthermore, we suggest that enhancing human capabilities, via building “centaur” intelligent systems, is not enough to achieve sustainable outcomes for complex systems. There is the need for chimera-like intelligent systems to achieve sustainable complex coevolutionary socio-technical-economic ecosystems, in the form of a Sustainability-designed Universal Intelligent Agent (SUIA).

A Universal Intelligent Agent is described as “ . . . a computational agent which outperforms all other intelligent agents over all possible environments” [112,134]. Sustainability-designed Universal Intelligent Agents (SUIAs) will emerge from the functional coupling of human intelligence, AI, and nonhuman biological intelligence, interacting as subsystems of the SUIA coevolutionary feedback loops. The SUIA will deliberately harness the complexity of the earth’s Biosphere to deal with uncertainty, expanding the conceptually new emerging complex metasystem’s phase spaces towards sustainable outcomes, while increasing its potential flexibility and fitness (efficiency) via a better exploration of new areas of the coevolutionary phase space and the exploitation of innovative, non-dominated optimal sets of solutions emerging as a result of such an exploration (Figure 3).

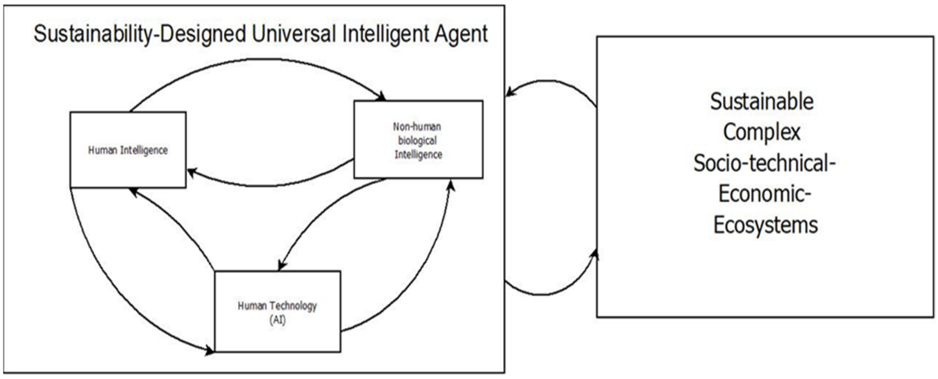

Figure 3. Sustainability-designed Universal Intelligent Agent (SUIA) for complex socio-technical-economic ecosystems.

The SUIA will comprise technological artifacts, and heuristic devices, for achieving sustainability, firstly by acknowledging the sine-qua-non, essential, strong functional coupling between human and nonhuman biological intelligence for humanity's survival purposes. From the SUIA will emerge coevolutionary strategies designed to maintain the short-term fitness and the evolutionary potential of both human-made systems and the Biosphere, achieving short-term goals, while maintaining long-term flexibility, thus solving multi-objective nonlinear dynamical optimization problems.

The strong functional coupling between the Biosphere and humanity has been evident, for as long as the human species has existed, in at least two main forms. The first refers to humanity's use of biological organisms and ecosystems as a source of energy, information, and materials for human consumption, well-being, and survival (e.g., agriculture), and the impact of the Anthropocene on the Biosphere, with, for instance, the generation and extinction of habitats, niches, and biological species as an outcome of direct or indirect human intervention. The SUIA will qualitatively change such dynamics, by emphasizing the pre-eminence of the Biosphere's health, since humanity's existence and well-being depends on the health of the Earth's ecosystems.

The second set of examples of strong interdependence is based on imitation, where a great deal of the most advanced human technological tools mimic, with varying degrees of success, biological processes and structures (e.g., [135–139]).

By acknowledging the functional coupling between the human species, its technology, and the rest of the Biosphere, the SUIA will not try to substitute biological intelligence with AI, nor non-human biological intelligence with human intelligence. Instead, the SUIA will increase the variety and size of phase spaces, enhancing both human and ecosystem capabilities for exploring and exploiting such phase spaces. Sustainability will then emerge from a non-zero-sum game as a sine-qua-non requirement, recognizing and harnessing the functional coupling of human societies and the Biosphere, since, with all its might, human technology is but a small subset of more than 4.2 billion years of sustainable biological engineering.

Among the main challenges to achieving truly sustainable complex coevolutionary systems is, at all levels of human societies, the cultural-philosophical-psychological shift needed to acknowledge that humanity is but a component of a 4.2 billion-year-old Biosphere, and also a (still) feasible solution among many to solve the riddle of the sustainability of life in the Universe. There is also the technological-ethical challenge of planning, implementing, harnessing, and evaluating, at all the hierarchical levels, the SUIA approach of agreeing, setting, and enforcing ethical and legal boundaries, based on respect, compassion, preservation, and awe for non-human biological solutions, and on the lessons and experience learned from more than ten thousand years of agriculture and animal husbandry practices.

8. Conclusions

As per the United Nations Environment Programme [140], an average of one new infectious disease affecting humans occurs every four months, transmitted to humans mostly from wildlife. Among such diseases, the COVID-19 syndemic emerged as a complex phenomenon of deep, severe, present, and future consequences, not only in the form of the great loss of precious, unique human lives, but in the harmful psychological, physiological, sociological, technological, and economic short- and long-term impacts for the whole of humanity. In the Anthropocene, the fate of both the human species and the Biosphere are intrinsically interdependent, with a healthy Biosphere providing, among a great number of other essential ecological services and tools, barriers against human disease. As a consequence of changes in soil use, biodiversity losses, human invasion and destruction of wildlife habitats, pollution, and climate change, and humanity's recklessness, arrogance, ignorance, greed, and disrespect against the Biosphere, these barriers have been severely damaged. The Biosphere will outlast the human species, but humans cannot survive without the ecosystems with which humanity coevolved. In the end, from an anthropocentric perspective, regardless of the form an ecological collapse will take, it will ultimately be paid for by human societies, since what is at stake is not the preservation of life on Earth, but the fate of the human species. More than ever, it is essentially true that during the post-COVID-19 syndemic period: " . . . we cannot go back to business as usual . . . we will need to rebuilt by working with Nature, not against it" [140]. The current crises have also brought about the best of humanity, as a conscious, intelligent, compassionate, technological species, to face the challenges of preserving its existence and well-being. A remarkable example and homage to human technological and scientific prowess is the very short time taken to develop multiple varieties of anti-COVID19 vaccines. Sustainability challenges cannot be successfully met without harnessing (vs. damaging, owning, monetizing, or controlling) the power of the Biosphere, including humanity and its technology, in the search for efficient, effective, flexible, sustainable solutions against humanity's current and future predicaments. The current syndemic has also resulted in a stronger sense of awareness of humanity's role in the Biosphere's stewardship. Such a role is accomplished through wisdom, knowledge, generosity, altruism, diversity, love, compassion, and the contemplation of life in all its forms and uniqueness with respect, awe, and reverence, as the non-structured guides for science and technology, mainly and foremost to ensure our own species' survival [141]. Let us then fulfill humanity´s duty as a technological species, playing a non-zero-sum game with the Biosphere to achieve truly sustainable complex coevolutionary socio-technical-economic ecosystems.

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