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Artificial Intelligence for Sustainable Complex Socio-Technical-Economic-Ecosystems.

Alejandro N. Martínez-García[1]*

[1] Tecnológico Nacional de México-Valle de Morelia, km 6.5. carretera Morelia-Salamanca s/n, Col. Los Ángeles, CP 58100, Morelia Michoacán, México; *alejandro.martinez.garcia@gmail.com

Abstract: The strong couplings among ecological, economic, social and technological processes explains 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 syndemics. Among complexification's essential 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 co-evolve 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, aiming at enhancing the co-evolutionary power of the Biosphere and its human subsystems. Giving the high-stakes, the need for effective, efficient, diverse solutions, their local-global, present-future effects, and their unforeseen short, medium and long-term impacts, achieving sustainable complex systems implies the need for Sustainability-designed Universal Intelligent Agents, harnessing the strong functional coupling between human, artificial and nonhuman biological intelligence in a no-zero-sum game to achieve sustainability.

Keywords: Artificial & Biological Intelligence, Complex Coevolutionary Systems Engineering. Sustainability, Multi-Objective Optimization, Sustainable Universal Intelligent Agents

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"…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].

1. Introduction

The concept of sustainability is increasingly considered as 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 and action, it is an ambiguous section from a paragraph inside a three-hundred pages' 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, have not been explicitly acknowledged. Here, we discuss the need for integrating artificial and

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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 time 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 the humanity's "extended phenotype" 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 7.8 billion people by July 2021 [11], with the associated increments on 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 in danger [13-15], all of which is translated as a reduction on the Biosphere's capacity for producing ecosystems services. Technology plays an essential role on The World Economic Forum's [16] lists of most likely and of greater impact global "critical threats to the world": infectious diseases, livelihood crises, extreme weather, climate action failure, cyberattacks, asset bubble bursts, biodiversity loss, human-made environmental disasters, adverse tech advances, cyberterrorism, digital power concentration and inequality, economic fragility, livelihood crises and 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 at the Anthropocene, ii) that humans are not part of 'Nature'; iii) and that change can be stopped or reversed, ignoring the evolutionary nonlinear dynamics of the Biosphere, where 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 could not 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 on biodiversity [13], and on the efficiency of, for instance, food production [12], anthropogenic phenomena such as the increased frequency of extreme meteors (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, thousands of homes, livelihoods and buildings lost, more than 10 million burned hectares and 1.25 billion dead animals) [17], and most importantly, the current global COVID-19 syndemics [18, 19], and their 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 co-evolutionary processes and interdependencies (lowering or eliminating barriers against interactions among ecosystems, people, business, institutions, and governments), helps to understand the emergence of phenomena such as globalization, economic, political and ideological crises, pandemics, technological revolutions, criminal and terrorism webs, climate change and its consequences, mass extinctions, greater urbanization, wealth, and

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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, components, etc.), where the greater the numbers, the more complex the system. Further consideration is due to the degree of conflict and incommensurability (not comparable with respect to magnitude and value) among systems' purposes and objectives, to 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 on its environment, with the system's behaviour emerging from its interdependency with its environment, and from functional couplings among its own and the semi-independent components it shares with other systems. From such changes also emerge known and unknown secondary effects that could propagate without control outside the system's boundaries [22]. Another consequence of nonlinear dynamics is that systems, their problems, their environments, and their phase spaces (dynamic, intractable multi-dimensional sets of all possible states for a given real-world complex system) [23] coevolve, with the consequent quantitative and qualitative changes on the system's dynamics [20].

The complexification of a given dynamical system is observed as epiphenomena, described as non-anticipated, hard to understand behaviours 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 behaviour, at a lower hierarchical level, of the system's components [24, 25, 26]. Further features of complexification are incomplete knowledge, uncertainty, unpredictability, asynchronicity (the value of a given state variable is not updated simultaneously in response to changes on auxiliary or control variables, which results in behavioural changes that apparently do not follow their 'cause'), greater difficulty for understanding, explaining and controlling present and future events, and a greater need for information in order to expand and maintain the system's dynamic phase space [27, 28, 29, 30, 31, 32], to meet challenges such as high performance, security, extreme environmental conditions [33] and, of course, to achieve sustainable outcomes [20]. 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 interdependencies (feedbacks or functional couplings) [34], in what could be described as nonlinear (vs proportional) dynamics. The semicircular, bidirectional arrows represent the strong, nonlinear, co-evolutionary couplings among the state variables, where each of the latter influences and is influenced by other variables and by the whole systems' dynamics. Among the outcomes of such dynamics are the need for complex systems approaches, and for ad hoc theoretical, mathematical and computational tools for describing, understanding and modifying those nonlinear dynamics [35, 20].

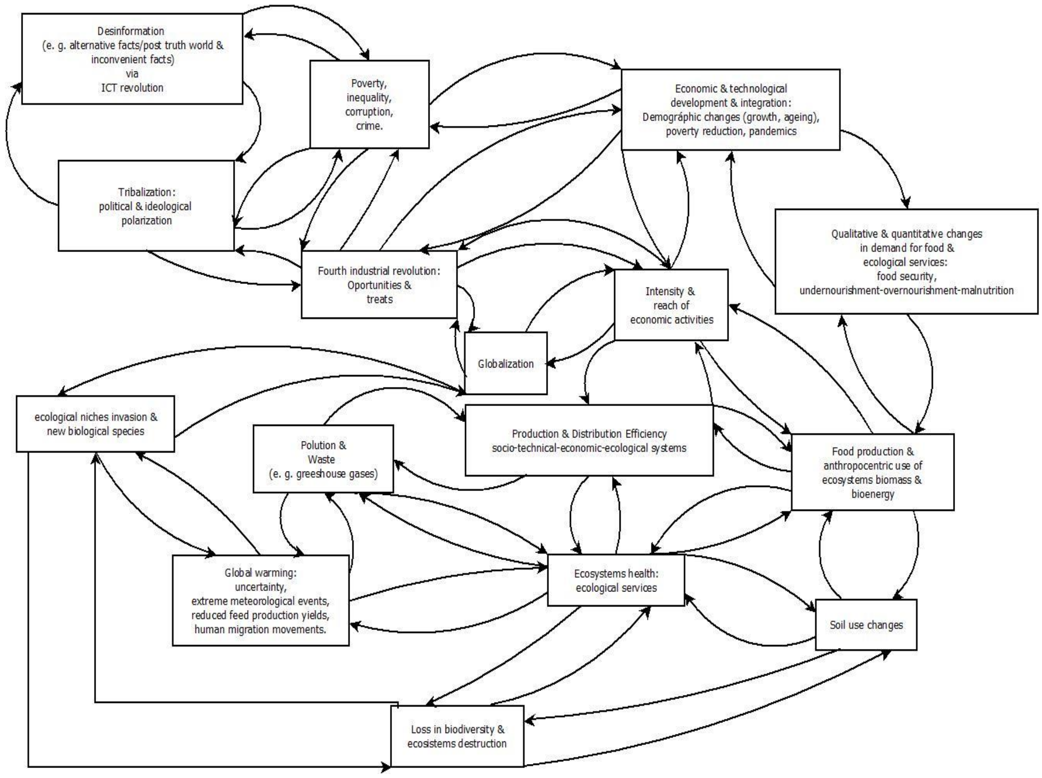

Figure 1. Some of the state variables and functional couplings related to sustainable human-made complex systems.

Nonlinear co-evolutionary processes such as the ones 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, economic, and 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 Organisation (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 sine qua non requirement for achieving the Agenda's purposes. The Agenda contains a set of seventeen Sustainable Development Goals (SDGs), which in turn are composed by one hundred and sixty-nine targets, to be achieved and evaluated by the year 2030 [37].

While the final version of the Agenda described its goals and targets as "…integrated and indivisible…" [37], it has been criticised because of a "…weak, fragmented and intermittent…" scientific input, that its number of goals and targets were too large and "unpractical", that the biophysical targets 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, 39, 40, 41]. Furthermore, the Agenda apparently lacked 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, 43, 44, 45, 46]).

Among the missing issues in dealing with the Agenda's design and implementation are:

- 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, the dynamic epiphenomena of complex socio-technical-economic-ecosystems' behaviour, which is defined by and defines the dynamic identity, in time and space, of such systems;
- features of complex systems, emerging from their non-linear nature, such as non-decomposability (parts of the system cannot be investigated separately from the rest, effectively preventing simplifications); asynchronous behaviour; components (or agents) that could respond differently (many degrees of freedom) to the same stimuli; increased likelihood of catastrophic, abrupt, large qualitative changes on the systems' behaviour; and irreversibility due to thermodynamics-quantum mechanics, and to the systems' sensitivity to initial conditions. Such features lead to the difficulty for understanding and controlling complex systems' behaviour, the impossibility of long-term, detailed predictions, and that problems, systems, environments, and intractable phase spaces co-evolve dynamically, meaning that each time a solution is found and implemented, the question changes, thus needing a new, different set of solutions [47, 48, 30, 31, 49, 50, 51, 25, 20];
- sustainability goals and targets are dynamic, nonlinear, constrained in time and space, semi-structured, frequently incommensurable, and in many cases 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…" [37, 20, 51, 40, 52];
- the acknowledgement of regional increments on the number of biological species, on ecosystems' net primary production, and on human's resource use efficiency, due to advances on science and technology [13, 53, 12, 54, 55, 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 co-evolutionary capacities of both human-made systems and the Biosphere;
- the fact that nonlinear change is not only unavoidable, but the essence of Nature's systems and their sustainability: a complex system is sustainable if it can preserve its capacity to coevolve with its 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.

As quintessential example of the kind of complex challenges of achieving the Agenda's goals and targets, are those arising from the nonlinear dynamics of one of the main focusses of the UNO's Agenda: extreme poverty reduction.

The World Resources Institute [59] projects 9.8 billion humans living on the planet by the year 2050. Among the Agenda's targets is the reduction of 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 as 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 syndemics (the pandemic, its associated economic crises, plus armed and social conflicts, and climate change). The World Bank calculates that between 88 and 115 million people worldwide did regress to extreme poverty in 2020, up to the likely future addition of 110 to 150 million more, for a total of up to 729 million people living in extreme poverty by the end of 2021 [65].

Poverty reduction contributed to the achievement of other of the Agenda's targets, such as higher labour productivity, greater mental capacity and longer, healthier lives, which in turn resulted in nonlinear increments on human population's size and income [37, 64, 65]. Other outcomes are nonlinear increments on 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 between 66 % and 170 %, depending on the product, compared to the year 2000 figures), and for ecological services [65, 59, 66, 67]. In turn, these outcomes increase the pressure (e.g., 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 capacity for providing such services [12, 68, 39, 59, 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, anthroponosis), and the production and management of waste [70, 71, 72, 39, 73, 65, 59].

While the whole of humanity suffers as 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 on child mortality, and the fight against diseases [44]. Paradoxically, the nonlinear dynamics described above have also resulted on 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. [74, 75, 69, 76, 77]) and on the awareness and impact of inequality among human societies [78] (Figure 2).

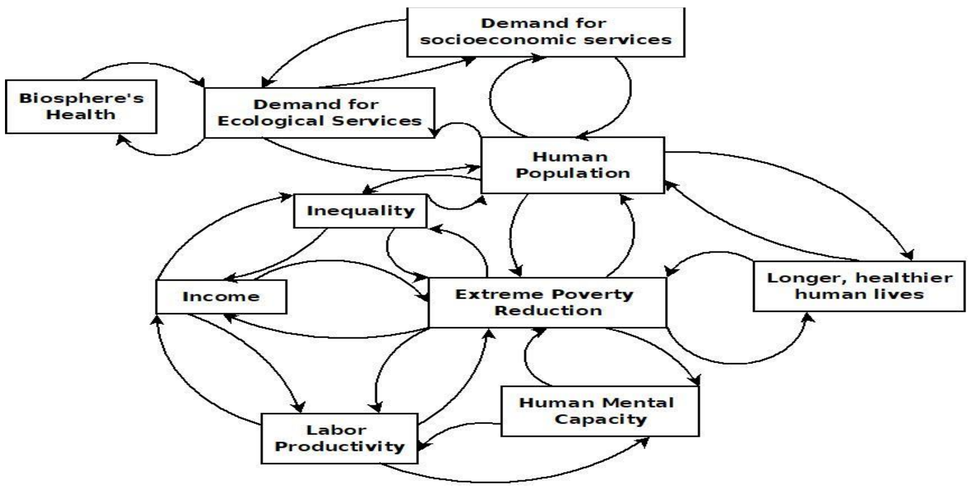

Figure 2. Nonlinear dynamics of extreme poverty reduction.

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 systems engineering sciences' contributions to achieve sustainable complex socio-technical-economic-ecosystems.

5. Engineering complex systems

If one considers: i) the high-stakes; ii) nonlinear dynamics and associated unpredictability, uncertainty, and their semi-structured, intractable, 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, achieving sustainable complex co-evolutionary socio-technical-economic-ecosystems is indeed a formidable and nonnegotiable complex challenge.

To face 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

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systems engineering for the holistic integration of social with 'hard' sciences [79]. While systems management emphasises sociocultural and managerial solutions to large-scale, complex, novel and heterogeneous technical issues [80], system engineering integrates, via tradeoffs and compromises, multiple purposes and objectives, and Science, Technology, Engineering, Mathematical and Medical disciplines (STEMM), "...to produce a coherent whole…", to identify, develop, implement, integrate and evaluate human cooperation and technology for the successful 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 large-scale complex project's success and reliability under financial, time, technological and social constraints [80]. Whatever limitations and contextual restrictions of systems management and engineering, and of 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

If one considers: i) the high-stakes; ii) nonlinear dynamics and associated unpredictability and uncertainty; iii) their semi-structured, intractable, incommensurable essence; iv) time, biological, technological, sociocultural, economic, ecological, and thermodynamical constraints; v) multiple stakeholders, shareholders and spatiotemporal dimensions; and vi) the urgent need for feasible, effective, efficient solutions, and their unforeseen short, medium and long-term impacts, achieving sustainable complex co-evolutionary socio-technical-economic-ecosystems is indeed a formidable and nonnegotiable complex challenge.

At the intersection of engineering, sustainability, and complexity sciences, sustainable complex co-evolutionary socio-technical-economic-ecosystems exhibit enough efficiency to exploit their dynamic phase space and enough flexibility to explore and coevolve with their environments [46]. Within this context, 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 socioeconomic environment for a given time horizon, via the generation of high quality, diverse, 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 with not ready-made solutions, and where human intuition and values (e.g., purposes, beliefs, happiness, self-fulfilment, well-being, etc.) are essential [82, 83]. Hence, sustainability engineering problems are semi-structured, implying a combination of both numerical procedures and intuitive, subjective judgement, 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, restricted access to materials, energy and information, and a given time horizon [84, 85, 86, 87, 20]. 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) [88, 46].

Therefore, from an engineering perspective, achieving sustainability is a non-linear, hard, semi-structured, constrained, dynamic, difficult multi-objective optimization problem, with conflicting objectives and subjective purposes, and intractable phase spaces [46]. To solve such a problem, one should start by defining the phase space where the human species could live, for as long as possible, in a co-evolutionary dynamic equilibrium with the ecosystems from which the species depends. This implies, among others, achieving acceptable standards of well-being and equity for all human individuals [89, 77], while

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preserving a phase space as large and diverse as possible to coevolve with a healthy Biosphere.

The above implies the generation of sets of tradeoff, nondominated 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 nondominated set of solutions could be considered as optimal options to solve the optimization problem, from which human decision-makers, with higher-level information (e.g., non-structured information such as preferences, attitudes, beliefs, ethical norms, etc.), classify, choose, and assume responsibility for the implemented solutions [20].

Because of its non-linear combinatorial essence, and the size of its dynamic phase space, sustainability problems are also difficult, computationally-hard, or intractable (no polynomial-time algorithm exists to solve this kind of problems), 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 exists at all [92, 93, 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 & Cohen [97] proposed that a suitable approach for solving complex problems of the kind described above comes from a subfield of Artificial Intelligence: 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], which 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 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, searching for and generating multiple solutions in parallel, without needing supplementary information of the problem, apart from the objective functions' target qualitative values (e.g. maximization, minimization) [98, 91]. MOEAs are flexible, adaptable, robust, effective, efficient, highly non-linear, massively multifaceted, stochastic, complex, able to deal with features such as discontinuities, multi-modality, disjoint feasible spaces, and noisy function evaluations; can exploit different fitness functions simultaneously, performing multiple direct parallel searches that generally results 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 [91, 90, 99, 100, 94, 101, 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 wellbeing 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 defence [103, 104]. PricewaterhouseCoopers [105] projected that the global Gross Domestic Product (GDP) will be 14 % higher (US$15.7 trillion) in 2030 due to the implementation of AI. Unsurprisingly, the field of AI is considered as a top Research & Development strategy for national governments around the world (e.g., [106]).

AI could be described as the field devoted to "…making machines intelligent, and intelligence is that quality that enables an entity to function appropriately and with

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foresight in its environment…" [107]. Depending on the kind of problems the tool is designed to solve, AI could be subdivided into general purpose (strong), and narrow AI. Narrow AI is supposedly based on intelligent biological behaviour to solve specific complex problems [108]. Among narrow AI's 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 human) [113].

While the development of the field of AI is a robust one, as with every human endeavour, it is not exempted from challenges and controversies. Among these, 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 [114, 115, 116, 104]. The later could be associated with the likelihood of increasing socio-economic inequality [116, 103], 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 of 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. While there has been some interest on developing AI computational hardware and software inspired by biological intelligence, such forms of computation do not result from in-deep understanding of the biological structures and processes from which biological intelligence emerge, since such understanding is at best metaphorical and incomplete [113, 119, 120, 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 [124, 119, 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 wellbeing; and of catastrophic forgetting, referring to the inability of AI (e.g. ANN) to learn multiple tasks sequentially (continuous learning) [127].

In turn, biological intelligence emerges from at least 4.5 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 could 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 behaviours. Instinctive behaviours appear intelligent, but are the outcome of evolutionary mechanisms designed for specific situations, and thus cannot

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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 behaviours that can be flexibly applied to completely new contexts, being such behaviours 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 non-linear processes among cells, tissues, structures, properties and functions of physiological systems, but also from co-evolutionary 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 behaviours, and is defined by any given biological organism's needs, allowing biological beings to continuously learn, master, and modify the things they need to survive [121].

Biological intelligence is described and expressed on senses, reflexes, learning, intuition, cognition, consciousness, and on 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 co-evolutionary cognitive environments, with no internal computations, representations or algorithms [120]. For biological intelligence, niche-constructed structures (including ecosystems, culture, and technology) function as extended co-evolutionary cognition tools ("extended phenotypes") [7, 8, 129], which greatly enhance biological intelligence capabilities to solve complex survival problems. Hence, biological intelligence is embodied, emerging from co-evolutionary 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 [130, 131, 32, 129, 121]. As an example of biological intelligence, human intelligence must be assessed in terms of its contribution to the survival of the species [129, 121].

While general AI goal is to mimic biological intelligence, a great deal of AI projects imitates processes of biological instinctive (not intelligent) behaviours. 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, 125, 124, 132, 121], and by the genetic, phenotypic, and functional variability of the biological co-evolutionary 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 subside the limitations of human intelligence. Cases where both kinds of intelligence bind with each other (e.g., the concept of 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 an integration are Daugherty & Wilson's [133] "fusion skills" concept, where narrow AI interacts with, amplifies, and its embodied to its human users in order to provide them with "superhuman capabilities" for solving complex problems; and Johnson & 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.

While this paper has discussed a Nature-inspired operational definition of sustainable complex systems, it is worth to try to elucidate what has been Nature´s answer to the sustainability problem. One 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 4.5 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 could 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 Agents (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 (SUIA) will emerge from the functional coupling of human intelligence, AI, and nonhuman biological intelligence, interacting as subsystems of the SUIA co-evolutionary 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 co-evolutionary phase space and the exploitation of innovative, nondominated optimal sets of solutions emerging as result of such an exploration (Figure 3).

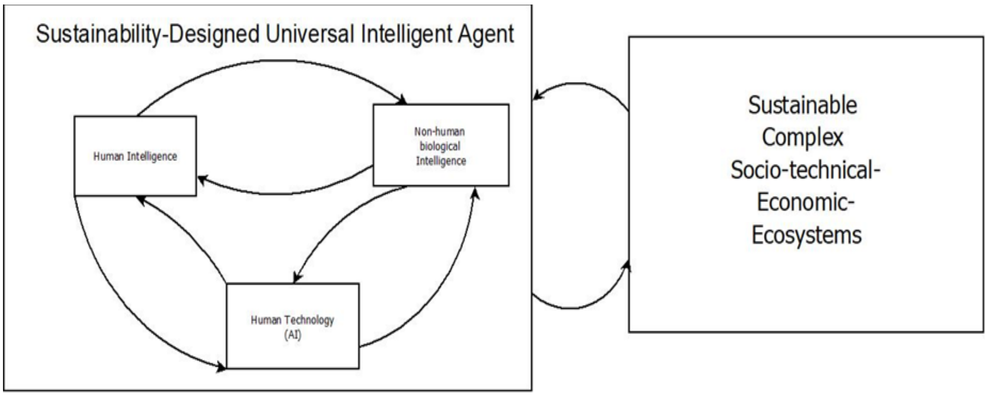

Figure 3. Sustainability-designed Universal Intelligent Agent (SUIA) for complex socio-technical-economic-ecosystems.

The SUIA will be a technological artifact 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 co-evolutionary 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 exists, 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, wellbeing, and survival, 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 change qualitatively such dynamics, by emphasizing the pre-

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eminence of the Biosphere's health, since humanity's existence and wellbeing depends on the health of the Earth's ecosystems.

The second set of examples of strong interdependence is imitation, where a great deal of the most advanced human technological tools mimic, with varied degrees of success, biological processes and structures [135]. Among the unaccountable examples of technology arising from the imitation and harnessing of biological processes, is the current exploration of several promising venues in the fight of the COVID-19 pandemic (e. g. 136, 137, 138, 141].

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 ecosystems 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 4.5 billion years of sustainable biological engineering.

Among the main challenges to achieve truly sustainable complex coevolutionary systems is the achievement, at all levels of human societies, of the cultural-philosophical-psychological shift needed to acknowledge that humanity is but a component of a 4.3 billion years 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, agreeing, setting and enforcing ethical and legal boundaries, on the basis of 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 syndemics, emerge as complex phenomena of deep, severe, present and future consequences, not only in the form of the exponential loss of precious, unique human lives, but on the harmful psychological, physiological, sociological, technological and economic short and long-term impacts for the whole of humanity. At 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, tools and barriers against human disease. As a consequence of changes on soil use, biodiversity losses, human invasion and destruction of wildlife habitats, pollution, climate change, and of humanity's recklessness, arrogance, ignorance, greed, and disrespect against the Biosphere, those barriers have been severely damaged. The Biosphere will outlast the human species, but humans cannot survive without the ecosystems the humanity coevolved with. At the end, from an anthropocentric perspective, whatever form an ecological collapse will take, will ultimately be paid 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 at the post-COVID-19 syndemics time: "…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 own existence and wellbeing. 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 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

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predicaments. The current syndemics has also result on a stronger sense of awareness of humanity's role as the Biosphere's stewardship, being such a role accomplished through wisdom, knowledge, generosity, altruism, diversity, love, and compassion, contemplating 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's then fulfil 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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