Anthropocene 30 (2020) 100245

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

How humans may co-exist with Earth? The case for suboptimal systems

Stéphane Grumbach[a], Olivier Hamant[b,*]

[a] INRIA & ENS Lyon, IXXI 46 Allée d'Italie, 69364 Lyon Cedex 07, France
[b] Laboratoire de Reproduction et Développement des Plantes, Université de Lyon, ENS de Lyon, UCBL, INRAE, CNRS, 46 Allée d'Italie, 69364 Lyon Cedex 07, France

ARTICLE INFO

Article history:
Received 8 September 2019
Received in revised form 17 April 2020
Accepted 18 April 2020
Available online 6 May 2020

Keywords:
Resilience
biosphere
technosphere
digital transformation
optimization
complex systems
feedback
human interactions

ABSTRACT

Human societies rely on rules to function, curbing the interests of individuals in favor of the interests of the population. A review of recent progress in biology and digital sciences suggests that such strategies might be universal: many living and technological systems favor the interests of the population to the detriment of individuals, at all scales. They behave in a suboptimal manner, restraining short-term performances while ensuring a high level of global resilience. This paper describes the features of such suboptimal systems. By synthesizing numerous examples within biological, and socio-cultural systems, we show how suboptimality might constitute a powerful source of inspiration to address the numerous trade-offs humanity is facing in the anthropocene. Should human societies curb their performance for the now anthropic ecosystems to be resilient? New research themes, such as soft law, agroecology, and planetary health, already echo suboptimal behaviors. These examples suggest that a better knowledge of suboptimal systems could help formalize a rational limit to human development towards sustainability, very much like the planetary boundaries for their Earth counterpart. Conversely, this synthesis also raises a question of whether human societies could be resilient without being suboptimal?

Contents

1. Introduction 1
2. Resilience as a function of suboptimality 3
3. Biological systems 4
4. Technological systems 5
5. Socio-cultural systems 5
6. The challenging trade-offs ahead 6
7. Conclusion 9
Competing interests 9
Acknowledgments 9
References 10

1. Introduction

The development of science and rational thinking in the modern era after the Renaissance and the Enlightenment led to societies that increased efficiency in all aspects of life and were obsessed by growth. They rejected tradition and praised technological progress, favored secularization and urbanization. They perceived their natural environment as controllable through scientific means and at the service of humanity. They also prioritized individualism, freedom and equality, education and health, as well as normative behaviors. This dominant ideology praises optimization in all sectors. Though this trend may have started earlier with the invention of farming tools, it reached its climax with Taylorism and the standardization of products, processes and tasks in assembly lines. This path has not been

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* Corresponding author.
E-mail addresses: stephane.grumbach@inria.fr (S. Grumbach), olivier.hamant@ens-lyon.fr (O. Hamant).

http://dx.doi.org/10.1016/j.ancene.2020.100245
2213-3054/

linear, wars in particular have been strong catalyzers of the race for optimization. In a ratchet-like mechanism, any gain in efficiency was never questioned when peace returned. Taylorism was, for instance, widely integrated in France during World War I, and its implementation was not challenged in the 1920s (Bonneuil and Fressoz, 2016).

Likewise, biological systems have constituted a strong source of inspiration for the amazing efficiency of their constructions. Biology offers multiple examples of systems that are extremely efficient. For instance, the motor that set bacterial flagella in motion has been compared to a human-engineered motor, with a rotor operating at ca. 10,000 rpm, allowing a remarkable motion of up to 60 cell lengths per second, which would correspond to a speed of 367 km/h for a human-size body (Macnab, 2003; Lowe et al., 1987).

Biomimetics has been used in many areas of engineering, to make materials with interesting properties for instance, and it plays an increasing role in information systems. Genetic algorithms, neural networks, viruses, ant colonizations are among the increasingly popular approaches for digital systems (Dorigo and Birattari, 2010). Biological models also have a particularly strong influence on the very fundamental field of Artificial Intelligence (Holland et al., 1992).

The positive enthusiasm associated with powerful technologies began fading in the mid twentieth century, following the potential for destruction permitted by technology and demonstrated during World War II. In the 1970s, a more profound awareness of the limits of the rational model supported by technological means and economic organization principles emerged. Thanks to the capacity to handle large amounts of data automatically, more holistic perspectives could be carried out. Forrester proposed a complex system approach to understand Earth (Forrester, 1971). This was then adapted to investigate the economic consequences of constraints on resources, addressed for the first time with such precision, in the very influential “Limits to Growth Report” (Meadows et al., 1972).

The complex system approach also questioned the engineering view of living systems, that the molecular biology revolution initially fueled (Nicholson, 2019). In his seminal paper on resilience and stability of ecological systems (Holling, 1973), Holling noted that ”our traditional view of natural systems might well be less a meaningful reality than a perceptual convenience”, opening the way to a new understanding of ecology, shifting from static equilibrium to dynamic conditions for persistence, across scales. Complex adaptive systems have been used to consider the sustainability of social-ecological systems (Dawson et al., 2010), as well as the way they evolve over time (Dearing et al., 2012).

The impact of human activities on the Earth ecosystem has since been the focus of intense research activities. Some landmark papers have appeared in the last decade, e.g., on the sixth mass extinction of species (Barnosky, 2011), the tipping point hypothesis in ecosystems (Barnosky, 2012), or the irreversible climate shift hypothesis (Steffen et al., 2018).

The converging conclusions of all these research efforts is that humanity's intense interaction with ecosystems may provoke unexpected large-scale consequences, damaging for human societies as well as to other species. Despite the succession of shocking numbers and doomsday predictions, however, the race towards optimization and resource exploitation has deviated very little. To take only one example, humanity has never burnt more coal than in the past decade (Smil, 2016).

Two ways are possible to approach this global challenge. First, technological progress should not be challenged, precisely because the environmental question also becomes an emergency. In that scenario, humanity would pursue its control over nature. For instance, the further consolidation of technology-driven solutions would offer answers to resource scarcity, pollution or the climate crisis, through the development of nanotechnologies, biotechnology, geo-engineering and smart cities, in the framework of the so-called ”good anthropocene” (Hamilton, 2016). In other words, because human intelligence, now more and more augmented with machine intelligence, is virtually limitless, it could compensate for the limits of Earth. This view is shared in many economic sectors, notably because a dramatic ecological issue might lead to important economic opportunities. It is also a prominent framework for several global ecological circles, notably those which associate the beginning of the anthropocene to the invention of Watt's machine, a technology. As a machine, Earth's problems could be fixed. The worldwide exchange of carbon quotas is a typical example of this optimization that can be qualified as ”total”, the entire Earth now thought of as an optimizable object.

In an alternative scenario, Earth's limits should be respected for the survival of humanity. This scenario means that socio-economic systems need to deviate from their current trajectory, including the race towards optimization. In that framework, technological solutions could be secondary; instead, the root of current socio-economic models should be challenged through alternative ways of life. This can be illustrated with the development of agroecology (vs. intensive agrosystems), slow and organic food (vs. fast and ultra-processed food), or the common goods (vs. private appropriation).

Both routes propose very different, but non-exclusive, answers to the central question of resilience. In the first scenario, increased individual performance would support and fuel societal and global resilience in the long term, by addition, and thus, it should be promoted. In the second scenario, increased individual performance would instead threaten global resilience, meaning that individual performance should be curbed.

This discussion is not new. Various theoretical models have been proposed to capture the conditions for resilience of socio-ecological systems. This is the case, for instance, in the stability landscape, which models the possible moves in a space with attraction basins of both the thresholds and the current state (Walker et al., 2004). Such models consider a set of attributes required for transformability, which includes the diversity of education and expertise, as well as trust and strengths in institutions, and speed and diversity of cross-scale communication. This distinction between the locality or the globality of equilibria is, in fact, found in classic economic theories. Pareto optimal, for instance, is a state in which no individual can increase their benefit without affecting others. Yet, it says nothing about the global benefit for the population.

A Chinese philosopher, Zhao Tingyang, revisited the very ancient concept of *Tianxia*, all under heaven, dating back from the Zhou dynasty circa 1000 BC (Zhao, 2005). This concept advocates harmonious coexistence mechanisms for the world order. Like many authors, Zhao Tingyang proposed a game theoretic approach to interactions. He called ”irrational” a strategy that has self-defeating consequences when universally adopted, and rational a strategy that takes into account the question of coexistence and is rewarding when universally adopted. Thus according to him, the present world strategy belongs to the irrational ones. Some of these tensions have also been analyzed in a classical socio-economic setting between the welfare of citizens and robust economic growth[1]. However, the natural ecosystem is generally ignored.

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[1] Joao Hrotkó, et al. Striking a Balance Between Well-Being and Growth: The 2018 Sustainable Economic Development Assessment. BCG July 2018. https://www.bcg.com/Images/BCG-SEDA-Striking-a-Balance-Between-Well-Being-July-2018-R_tcm9-196740.pdf

This paper revisits the concept of resilience in relation to the tension between individual and collective interests. To do so, we define the concept of suboptimality as a state in which randomness, heterogeneity, slowness, redundancy and other forms of inefficiencies at individual levels lead to robust outcomes. Suboptimality is achieved through interdependencies, leading to variants of second-best optima at the global scale. A synthesis of numerous examples aims to show the correlation between the resilience capacity of a system and the suboptimality reserved to individuals.

The paper proceeds in the following way. We first consider biological systems and show that such complex suboptimal mechanisms are present at all scales. Next we review technological systems, and in particular the Internet, showing that the principle of suboptimality is widely used at all levels to ensure long term stability of computational systems. More generally, we then present how suboptimality is a fundamental aspect of other large distributed systems. Cultural, social as well as economic systems also make use of similar mechanisms for their resilience. Furthermore, we outline challenging trade-offs between individual and society, and between suboptimality and optimality. Through their evolution, humans have apparently converged towards suboptimality to promote the long-term resilience of their societies. The anthoprocene, an era in which human activity has dominated Earth's functioning (Ruddiman et al., 2015), now questions our ability to promote resilience at a larger, planetary, scale. Finally, we propose suboptimality as a possible path towards resilience for humans in the anthropocene future.

2. Resilience as a function of suboptimality

The claim for suboptimality relies on the idea that local inefficiencies, in the form of heterogeneity, randomness, slowness, incoherence, or redundancy, can fuel adaptability and thus resilience in the long term. For the sake of simplicity, we initially focus on heterogeneity and its relation to the resilience of systems.

Charles Darwin's theory of evolution is in essence based on heterogeneity, i.e., on differences between individuals. Selecting the most adapted individuals to a given environment implies that not everyone is optimally adapted. The source of such suboptimality resides in part in the presence of random mutations in the populations, preventing homogeneity and providing a medium for natural selection. This also applies to selective breeding: only a diverse population can provide new individuals with advantages and increased fitness to their environment (or apparent benefits in agriculture). In short, from an evolutionary point of view, an element of randomness, and thus inefficiency at the population scale, is the price to pay to allow adaptation to variable environments, and thus resilience.

Our thesis is that if we consider the collective resilience as a function of the heterogeneity of the population, homogeneity does not necessarily correspond to an optimum. Instead, collective resilience reaches a peak with a certain degree of heterogeneity, meaning that it decreases when heterogeneity either decreases towards a homogeneous population (clones), or on the contrary increases towards a fully heterogeneous population (incompatible) as shown in Fig. 1. In other words, suboptimality in biological populations addresses the question of resilience by taking into account the complexity associated with different temporal and spatial scales: homogeneity might be a productive strategy in the short term and for a small group of individuals, but would not ensure the long-term survival of a larger population; conversely, heterogeneity has a cost locally in the short term (e.g., by preventing survival of certain individuals), but is a well-known adaptive strategy in the long term. In the most extreme case, homogeneity may increase performance in the short term over resilience in the long term (as in transient clones of parasites), whereas heterogeneity would increase resilience in the long term over performance in the short term.

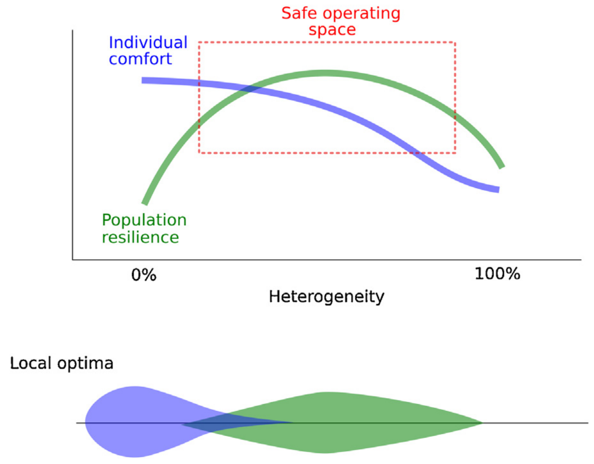

Fig. 1. Safe operating suboptimal regions vs individual optimum.

Quantifying such trade-offs is often not easy, because of the difficulty in collecting the right data. The development of quantitative approaches in biology now opens the path for its formal investigation. The case of organ reproducibility provides a clear example of the global benefits of suboptimality. Organs need to be reproducible. For instance, flowers from the same species need to have the same shape and size to be pollinated by the same type of insects. Does this mean that plant organs are built like objects in an assembly line? On the contrary, organs are made of cells with variable size and shape. Not only does such noise allow them to adapt to environmental fluctuations, but the associated mechanical conflicts in the tissue may even serve as a proprioceptive mechanism for the organ to know when to stop growing. In other words, an apparent weakness (cell variability) promotes the autonomous shaping of organs, ultimately leading to reproducible shapes, despite environmental fluctuations (Hong et al., 2018).

Such phenomena can be observed outside of biology. The analysis of road traffic for instance provides a simple illustration of the discrepancy between the highest individual interest (highest speed), and the suboptimal region, where fuel consumption, pollutants and accidents are minimal (Fig. 2, (Hosseinlou et al., 2015)).

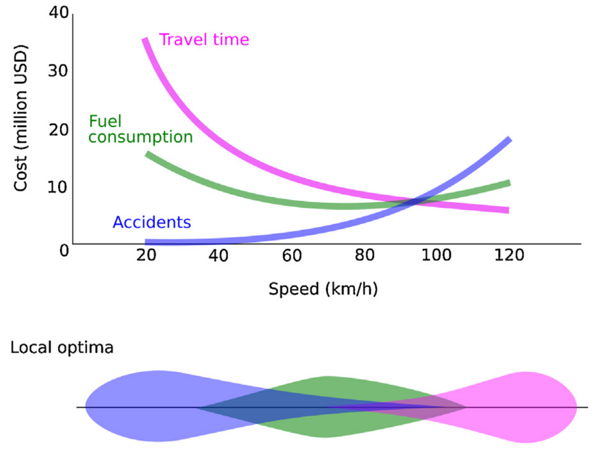

Fig. 2. Traffic trade-offs [Hosseinlou et al., 2015].

Box 1. Complex systems, a short definition

Complex systems are formed by large numbers of entities that interact with each other dynamically (Bar-Yam, 2002). The brain, as a group of interacting neurones, ant colonies, or various social systems constitute classical examples. Complex systems result from the interactions of their constituents, which exchange matter, energy or information, as well as their interaction with their environment. They are dynamic, usually exhibit non-linear behaviors and are continuously adapting to changes. Complex systems are learning and remembering from their past. Their knowledge is fully distributed among the constituents, each of which stores a very limited amount of the global knowledge, and so is the control of the system. A key characteristic of complex systems is the emergence of properties, such as structures and order, at a higher scale of organization. For instance, at the end of a concert, the synchronous clapping of the audience is not determined by one person, it is emerging from the interactions between neighboring spectators. Similarly, ant farm architecture emerges from interactions between ants, and thinking emerges from local interactions between adjacent neurones in the brain. Some very general regulation mechanisms are at play with feedback loops, which either enhance (positive feedback), or inhibit (negative feedback) phenomena.

Examples of the tension between personal interest, leading to homogeneous behavior, and collective interest, that would favor diversity, abound in social systems. Various fundamental aspects such as the distribution of wealth, tax systems, education and health, or the political legitimacy of decisions, all relate to trade-offs around such tensions. Transport systems in cities offer a simple illustration of such phenomena. In the twentieth century, they have favored private cars, which are more agile, adaptable and sometimes faster, than collective means, but resulting in various imbalances, such as traffic jam and pollution, that do not admit simple solutions. Interestingly, increasing the number of car lanes for instance, although it might provide a relief in the short term, actually leads to more traffic jams in the long term, as shown by Braess paradox (Braess, 1968). This is a very well known phenomenon, similar to Jevons paradox which showed in the nineteenth century that the increase of efficiency of the machines, do not lead to a decrease of coal consumption, but instead to a larger adoption of machines (Jevons, 1865).

Very often, the complex systems approach offers counter-intuitive solutions (see the definition of Complex systems in Box 1), as in the case of organ reproducibility which, surprisingly, requires cell variability. Similarly, it is now well established, thanks to fluid mechanics, that traffic jams are not resolved by adding more lanes, but instead by imposing reduced car speed to promote more uniform, and thus more fluid, global behaviors.

Although we discussed the relative contribution of homogeneity and heterogeneity in the resilience of systems, the same conclusions can easily be extended to randomness, slowness, fluctuations, redundancy, incoherences. In all these cases, a system would experience a form of inefficiency locally, but this would also fuel adaptability in the long term and for the global population. We consider in greater detail biological systems, which offer many examples of suboptimal behaviors at all scales.

3. Biological systems

Health offers many examples of trade-offs between individual and collective interests. We start with a trivial, but controversial, example of an individual who is sterile because of a genetic mutation. Thanks to progress in clinical research, that person can become fertile: the health sector favors individual comfort. This also means that the mutation is maintained in the population, however, and may be passed on through generations. Although this might not be an issue in contemporary societies, it may threaten the resilience of future populations, in case such services would for instance not be offered to future generations.

This scenario is actually more complex. Carrying a genetic mutation can also become beneficial for the population. Taking the case of sickle cell anemia, in some areas of the world where malaria is frequent, 10% to 40% of the population also carries a mutation that triggers sickle cell anemia. This apparent anomaly can be explained: sickle hemoglobin (which causes the sickle cell anemia syndrome) promotes the expression of a protein called heme oxygenase-1, which produces more carbon monoxide, a molecule that protects against malaria (Ferreira et al., 2011). This example shows an apparent disadvantage that also provides a positive gain, in a suboptimal scenario.

Now, one may wonder if this only applies to populations, thus restricting suboptimality in biology to global behaviors. Is biology also suboptimal at the microscale? Recent discoveries in the field of developmental biology support that hypothesis. For instance, it is well established that shape changes during embryogenesis rely on asymmetries, in the form of outgrowth of groups of cells (e.g., during the formation of new limbs), death of selected cells (e.g., during the formation of fingers) or cell contraction and tissue folding (e.g., during the formation of the neural tube). Evidence now exists that such events are not only the consequence of fully stereotyped processes, but instead are also primed by stochastic fluctuations between cells (Singh et al., 2010; Wernet et al., 2006; Laslo et al., 2006; Gupta et al., 2011). In other words, heterogeneity is pre-existing through random fluctuations, and as in Darwin's theory, cells are selected to amplify existing heterogeneities, leading to apparently consistent and well-choreographed processes in the end. Interestingly, this is observed both in animals (Martin et al., 2009), and in plants (Uyttewaal et al., 2012), further supporting the generality of such mechanisms. This non-deterministic mechanism has a strong evolutive advantage: it maintains the cell competence to acquire a wide spectrum of fates in the long term. A deterministic approach would have instead been more efficient in the short term by ascribing a function to each cell from the start, but it would have hindered any further adaptation to external fluctuations. Such behavior has been formally demonstrated in several cases, including the differentiation of cells into neurones in Drosophila (Heitzler and Simpson, 1991).

It therefore appears that biology usually does not fuel homogeneity, despite the apparent reproducibility of shapes in nature. In fact, even genetically identical organisms in stable environments vary: a degree of randomness in gene expression is sufficient to generate some level of diversity. This sometimes refers to “incomplete penetrance”: individuals with the exact same mutation may have different appearance or behavior because of the presence of natural fluctuations in biological processes, such as protein synthesis. Conversely, these fluctuations are used in biological processes to generate variable shapes and behaviors. Modern biology thus increasingly embeds an element of probability (Chang et al., 2008). This situation can have very practical consequences, for instance in biomedical science: the presence of noise in gene circuits (e.g., fluctuations in protein synthesis) can enable subpopulations of cells to become transiently resistant to antibiotics, thus allowing their survival (Rotem et al., 2010).

How can one explain such widespread stochastic behavior? The answer to that question is, in fact, surprisingly simple: to generate noise at the microscale, one needs to have a low number of molecules. To take an example, if a cell contains thousand copies of a protein that acidifies the cell content, small fluctuations in the number of proteins would have little effect on the cell acidity because the large number of proteins buffer such fluctuations. If instead a cell only contains two or three copies of that protein, any changes in protein content would generate huge fluctuations in acidity. With the development of single molecule tracking, such fluctuations can now be investigated in the lab, revealing that many proteins are indeed in low copy number, and thus are in principle amenable to generate stochastic behaviors (Blake et al., 2003; Raser and O'Shea, 2004; Newman et al., 2006).

With the eyes of an engineer, this behavior may appear as inefficient. Yet, the fluctuations such systems generate is key to the adaptability of organisms to variations in their environment. In other words, suboptimality at the microscale is a building block for the resilience at the macroscale. This recalls Ashby's theory on ”requisite variety” which states that a system facing fluctuating and unpredictable aggressions can maintain its stable states only if the diversity of the available responses is actively maintained (Ashby, 1991).

Altogether, these examples illustrate how biology is fundamentally suboptimal, at all scales. Next we review non-living systems where quantitative data are available, and investigate their suboptimality.

4. Technological systems

Technologies allow humans to master elements, such as fire, energy, matter, living organisms or information to name a few. They often contribute to facilitating tasks by optimizing their functions. They range from very fundamental shapes, such as knifes or wheels, to complex systems such as water adduction mechanisms for cities, energy grids, or Web services. The integration of all technological systems, ore extraction, industrial transformation, transportation, agriculture, chemistry, genetic modification, etc. has led to the all-encompassing concept of technosphere (Haff, 2014), reflecting their complex interdependencies. Humanity, with its present extension of more than 7 billion beings, has become as dependent on the technosphere as it is on the other spheres of the natural environment, such as the biosphere or the atmosphere.

Unequivocally, technology has been a key driver of the human race towards optimization. Yet, associating technology with ”optimality” is over-simplistic. Indeed, the suboptimal mechanisms, which we just observed at various scales in the biosphere, are also at play in the technosphere for large distributed systems.

Let us focus on the digital layer which plays an increasing role in the control of the technosphere. Finance, transportation, energy, defense, social interactions, access to news or knowledge, are activities which are now taking place at various degrees over the Internet. The recent explosion in the capacity of algorithms, which handle the information exchanged by machines, can now ensure real-time decision for extremely complex tasks. This capacity explains both the rapid expansion of automatic control, as well as the expectations of society for their promises to develop ”smart” environments, pruned of human errors.

The Internet was developed as a means to connect networks of machines globally. It connects an unbounded number of different networks, most of them owned by private companies, that ensure very different tasks. This system is fully distributed and has no centralized control. The connection is made possible by essentially two types of standards: exchange protocols and addresses in the network, such as IP addresses and domain names. Packets consisting of a header for the destination and a payload for the transported data are exchanged between machines.

The simple universal protocol suite, TCP/IP, regulates how packets travel through the network from one machine to another, through intermediate machines that relay them. The service is unreliable and the IP protocol just ensures best effort. Significant errors are possible: the data can be corrupted, packets can be lost or duplicated. The network is dynamic, changing continuously with constant failures of nodes. The path that packets take are not remembered, so consecutive packets can be routed to the same destination through very different paths. Packets are then reordered with TCP but with possible delays.

In fact, most communication systems ensure robustness to the detriment of the fate of individual packets. This was already the case of legacy postal services, efficient on average, but with no guarantees for individual letters or packets. Radio communication systems also make use of diverse communication paths, using recombination techniques for altered messages for instance (Miu et al., 2005). In short, the suboptimal handling of individual entities ensures the resilience of global communication networks.

With the advent of Web services, supported by large distributed systems, technological problems became more complex, and suboptimality was not avoided. Instead, it became even more essential.

Data systems available everywhere anytime to a large number of users, such as search engines, social networks or online market places, rely on distributed systems. They rely on data that are duplicated on different sites to allow massive concurrent access. These systems are subject to failures that can result in partitions of the network. Brewer's theorem states that such distributed systems, which can operate despite lost messages, cannot simultaneously ensure (i) consistency, that is access to the most recent data, and (ii) availability, that is the guarantee to receive a response, not necessarily the most recent (Gilbert and Lynch, 2002). Availability, which is associated with the quality of service for the user, is ensured to the detriment of accuracy. Different users will get different responses for the same query, thus potentially introducing diversity in their behaviors. So here again, the correlation between suboptimality, diversity, robustness and resilience is apparent.

This synthesis points to an alternative way to be suboptimal, i.e. through algorithms. Algorithms could be viewed as efficient tools that enable process optimization, making the best use of available resources, increasing the level of reliability and safety, and avoiding human errors. Consistently, computer science is massively devoted to optimization. Thus, is there room for suboptimal behavior? Here again, we observe that algorithms foster suboptimality in many ways. The reason is related to the optimization of the algorithms themselves. Many of the practical problems that humans want to solve using algorithms are rather complex. A brute force strategy to find the best solutions would be too costly from the computational point of view. Most of the time, approximate solutions, at a reasonable distance from the optimal solution, are computable with a substantial gain of resources (Vazirani, 2013). A fundamental class of problems, called NP-hard optimization problems, are very frequent in practice and admit good solutions with approximation algorithms (Hochba, 1997). They include allocation problems such as scheduling classes, professors and rooms in a school, or transportation logistic, for instance. Here again, technical issues result in a suboptimal treatment of cases that contribute to a diversity of individual answers and behaviors.

5. Socio-cultural systems

The suboptimality principle may play a fundamental role beyond biological and technological systems. This section describes some examples of systems exhibiting rather similar suboptimal phenomena. The most obvious is probably human language and communication. The meaning of sentences is in general ambiguous. To quote the French linguist Antoine Culioli, ”comprehension is only a particular case of misunderstanding”. Humans benefit from the ambiguity of language more globally, in a whole range of aspects from psychology to imagination, enabling resonance (Rosa, 2016) between divergent points of view, and thus construction of common projects at all scales (Berninger, 2012; Harari, 2014).

Beyond spoken languages, writing also contains an element of suboptimality: people write characters differently. This is used for authentication of the signature, as well as in criminal investigations to assess identities. Yet, everyone can, in general, understand what is written despite these heterogeneities. At the level of a text, typos usually do not hinder the comprehension of a text, as our brain usually captures the word rather than the individual letters. Such suboptimal communication means extend to non-verbal communication too (Descola, 2018).

Beyond communication, human societies have invented rules and regulations that integrate suboptimality, at least to some extent. For instance, in many sectors, information is accessible, but societies do not make use of that information. Census data for instance cannot be used for any other purpose than establishing global knowledge on the population. Similarly, evidence obtained illegally cannot be used in court in most legal systems; journalists cannot be constrained to reveal the origin of their sources; physicians are protected by patient confidentiality. These rules might at times seem costly, when considering the individual benefit, but they balance a trade-off between the interest of a given individual situation in favor of the system functioning as a whole.

Challenging optimization has also been a subject for computational modeling in economics, notably through the concept of viability: a system is viable if one can find a path through which all constraints are satisfied indefinitely. In other words, instead of setting fixed parameters, they are freely evolving within defined borders, meaning that variables can adapt to the evolution of the system over time. This corresponds to a situation where only second-best optima are reached. It is suboptimal, and the cost of not being optimal is compensated by increased adaptability and resilience. In that framework, a crisis corresponds to a limited period of time during which no viable path can be found. One of the objectives of the formalization of viability is to identify such crisis periods and minimize their duration (Doyen and Saint-Pierre, 1997). Beyond economics, viability approaches have been applied to demography, for instance to help determine whether to have children or not (Bonneuil and Saint-Pierre, 2008), and in biology to study the maintenance of genetic diversity in populations (Bonneuil and Saint-Pierre, 2000).

Beyond the obvious resonance with the social (vs. liberal) economic model, suboptimality also questions the degree of required decentralization and personalization for societies to become resilient. The American political economist Elinor Ostrom considered such tensions in her work on common-pool resources and institutions (Ostrom et al., 1994). She explored the relative contributions of governments and self-organized user communities to manage resources, showing, against dominant beliefs, that the former could lead to resources destruction, while the latter could very well succeed in maintaining sustainable consumption (Ostrom, 2009). Contradicting the simplistic scenario of the tragedy of the commons, the mechanisms at stake relate to suboptimal appropriation, as well as shared usage of resources (Hardin, 1968).

Suboptimality offers an alternative to the shortcoming of the reductionist approach in all sectors. For instance, it echoes the progressive withdrawal of universalism that prevailed, e.g., in colonial times. For the Chinese philosopher Zhao Tingyang, politics become the art of co-existence by transformation of hostility into hospitality. He asserted that we ”have to be built on the broader foundation of a compatible universalism that includes all civilizations - not an exclusive unilateral claim of one civilization to universality”[2] .

In terms of resources, after years of intensive practices that have led to soil sterilization worldwide, and thus a form of desertification, suboptimality is also gaining momentum in agriculture. In this case, and beyond the environmental question, the possible gains in performance in the short term through optimization are even questionable: the apparent increase in cereal yield for instance was allowed by the massive use of fossil energy to generate fertilizers (through the Haber process), to irrigate the soils and to maneuver machines. In fact, in France, intensive agriculture has been exhibiting an energy deficit since 1970: it produces fewer calories than it requires to function (Bonneuil and Fressoz, 2016). In contrast, agroecological practices are less demanding in resources, permaculture maintains a constant coverage of the soil during the year and thus allows its survival, heterogeneous cocultures allow the production of different crops on the same sites, and thus interspecies cooperation. All these different strategies revisit the natural functions of an ecosystem, and now serve as models for a resilient agriculture (Griffon, 2006).

6. The challenging trade-offs ahead

As suggested by the review above, large distributed systems apparently use suboptimal behavior for their resilience. One would thus expect that this behavior will also naturally apply to humans and their response to the challenges of the anthropocene. The example of agroecology, mentioned above, suggests that emerging solutions may indeed involve suboptimality, at least to some degree.

Several new elements must be considered, however, when applied to humans. First, the question of resilience in the anthropocene is now a planetary one. Can humans proactively deploy suboptimal strategies, even if the crisis is not apparent among their local environment yet? Second, in contrast to other natural systems and entities, humans and human societies have the power to project their trajectory in a speculative future. This power represents a major difference between natural and cultural systems. For instance, humans have developed elaborate education systems to build a society of knowledge. They are able to create computational models predicting future behaviors, in all sectors. Dealing with such a global problem may likely be essential. Conversely, ideological biases, from the past and projected future, may skew the predictions, and further constrain the degree of acceptable suboptimality. Guessing whether suboptimal answers to the anthropocene will be put forward or not is thus difficult, and even, whether these would be more apt than other strategies. It remains that humanity will have to face major trade-offs in the future. At least, the formalization of suboptimality offers a starting point to question the various strategies to face them.

Michel Foucault considered the complex dependency between power techniques and forms of knowledge (Lemke, 2001). He proposed the concept of bio-politics (Foucault et al., 2008), so relevant today with the increasing government of global digital platforms that control access to information and knowledge and softly nudge people to new behaviors. In a seminal paper, Chandler (Chandler, 2014) considered the implications of resilience for

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[2] Zhao Tingyang. Can this ancient Chinese philosophy save us from global chaos? Washington Post. 07.02.2018. https://www.washingtonpost.com/news/theworldpost/wp/2018/02/07/tianxia/

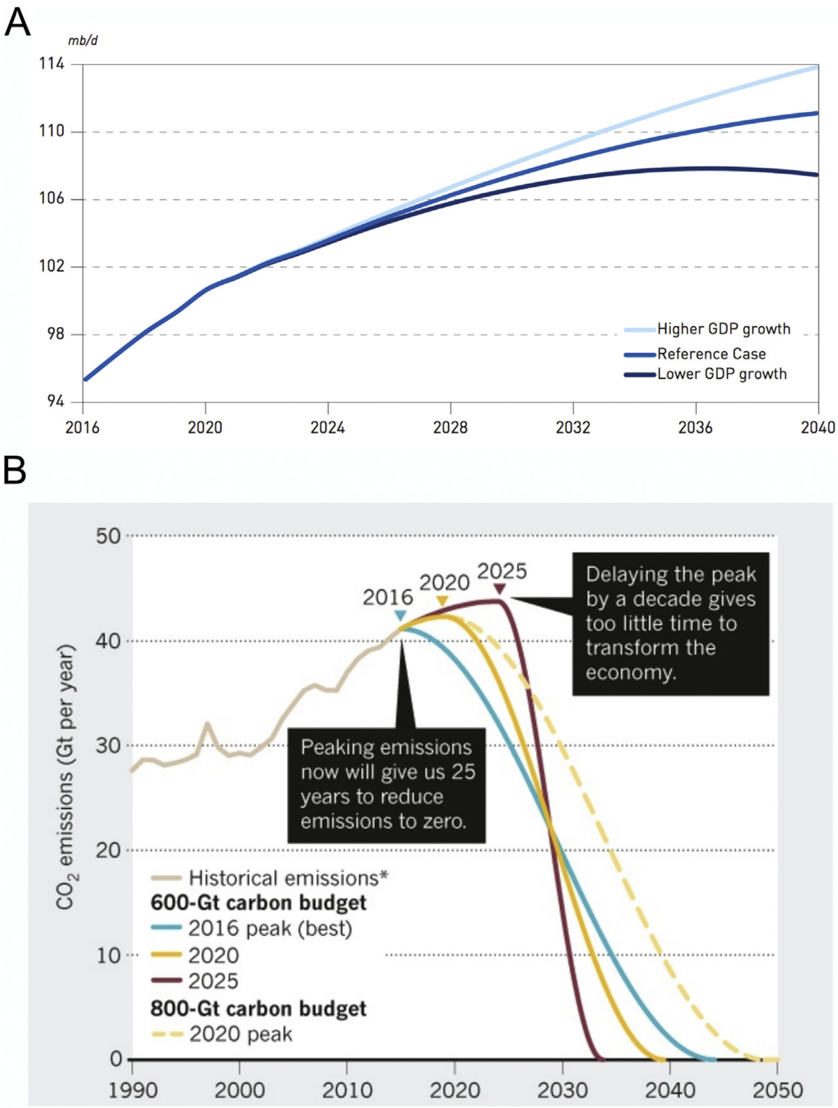

Fig. 3. World oil demand vs carbon crunch.

governance, showing that "resilience-thinking, which posits an ontology of general or emergent complexity, can be seen as a distinctive third governmental episteme and contrasted with liberal and neoliberal ways of conceiving life as complex." Such an integrative approach to cyberspace is emerging in East Asia, in particular in Japan with the Society 5.0 program, and in China with the social scoring experiments. These systems make full use of available data to monitor the interactions of people with the socio-ecosystem, and nudge their behavior.

To elaborate, we start with a classic discrepancy in environmental policy. The organisation of human societies today, and their current projections into the future, are not aligned with the scientific knowledge on the precarious situation of the natural ecosystem. This divergence can be easily illustrated with the climate crisis. Fig. 3A shows the projections of OPEC for the world oil demand depending upon economic growth sensitivities[3] . Fig. 3B on the other hand shows various scenarios to use the carbon budget of around 600 gigatonnes of carbon dioxide left to emit before the planet warms dangerously by more than 1.5-2°C (Figueres et al., 2017). One fundamental aspect of this divergence is precisely related to the trade-off between individual and collective interests. An optimal way to deal with the question of such natural resources would be to customize the needs to the available stock, e.g., by increasing the stock (shale gas, biofuels,...) and by reducing the needs (e.g., smart cities, sober machines). As described earlier, the risk with this strategy is to create new needs and attractions, as in Jevon's paradox, and thus further amplify the discrepancy between stocks and needs. A suboptimal way to approach this question would be to curb the societal need to such resources, through economic regulations (e.g., tax) or through environmental regulations (e.g., protected areas). See Fig. 4 for a global presentation of the trade-offs between the benefits of individuals, societies (past, present and future) and ecosystems. These trade-off also entail new forms of governance, that include suprasocietal voices, i.e. that of future generations (Feinberg, 1974) and that of the ecosystems (Wise, 2014). Integrating nature in all economic

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[3] World Oil Outlook 2040. OPEC 2017. https://www.opec.org/opec_web/flipbook/WOO2017/WOO2017/assets/common/downloads/WOO%202017.pdf

[4] Legal rights have been attributed to rivers recently in New Zealand and India. See for instance: Roy, Eleanor Ainge. "New Zealand river granted same legal rights as human being." The Guardian 16 (2017). Safi, Michael. "Ganges and Yamuna rivers granted same legal rights as human beings." The Guardian 21 (2017).

Table 1
Suboptimal solutions to complex issues

Questions & concepts	Optimal answer (reductionist)	Suboptimal answer (systemic &adaptive)
Climate crisis	Geo-engineering, electric cars, renewable energy	All of below
Shortage of resources	Nanotechnologies, smartness, bio-technologies	Frugality, bio-economy, birth control
Food security	Intensive agro-systems, precision agriculture	Agro-ecology, permaculture, natural parks
Economic crisis	Increased efficiency and competition, innovation	Slow movement, degrowth, inclusive social model
Common goods	Privatization and global regulation	Protected areas, shared usage and regulation, soft law
Justice	Include the maximum number of evidence	Exclude illegally obtained evidence
Medicine	Personalized medicine, efficient cures (e.g., antibiotics)	Prophylaxis (e.g., vaccine), planetary health
Robust management	Pyramidal, centralized, efficient &competitive	Loosely coupled systems, autonomy, self-governance
Robust decision making	Multi-criteria approach	Viability, holistic, long term assembly
Robust communication	Precise and concise (e.g., scientific writing)	Redundant, heterogeneous (e.g., human, telecom)

and political decisions was already rooted in Michel Serres' natural contract (Serres, 1995). In these footsteps, the inclusion of trees (Stone, 1972) and rivers[4] as legal entities is currently debated. Attempts to consider such large-scale issues - both temporal and spatial - are also taking the form of democratic innovations, such as the ”assembly of the long term” (Bourg, 2011).

Beyond our relation to natural resources, the anthropocene is shifting the trade-offs to the planetary scale in other sectors too, while also confronting technological progress. One example is health policy. Like many sectors, this field has two sides, individual health and population health, which are mostly perceived as independent concepts, handled by different social organizations. Note that their interdependency remains strong, and addressed in fields such as epidemiology. The relationships between individual health and population health varies (Arah, 2009). For instance, a high rate of immunization through vaccines is usually viewed as essential for the protection of populations (and thus individuals). Yet, this may conflict individual beliefs, in a typical suboptimal scenario (Pronyk et al., 2019).

The current trend in health policy might be more oriented towards individual health with less care of the population as a whole. The use of pharmaceutical drugs, such as antibiotics for instance, can result in harmful effects at a global scale, while it might prove useful to cure a given individual (Davies and Davies, 2010). Similarly, personalized medicine (also called precision medicine) presupposes that individual health is a building block for public health, in a typical reductionist framework (Schork, 2015). In contrast, a suboptimal scenario would favor the health of the population, a form of ”imprecision medicine”, over the health of individuals. Interestingly, the latter scenario could include the emerging anthropocenic trade-offs. In fact, it is already at play with the concept of planetary health, where health includes, beyond the human population, dimensions of the natural ecosystem as a whole (Mallee, 2017).

Society is still struggling to make sizable progress in that area. For instance, the report of the Rockefeller Foundation and the Lancet Commission on planetary health makes a severe statement about the global handling of health: ”We have been mortgaging the health of future generations to realise economic and development gains in the present” (Whitmee et al., 2015). A key challenge for the future will be to find a viable path between acceptable approaches to individual health, while securing the health of populations and the ecosystems. This question basically calls for suboptimal, more inclusive, approaches to health.

Beyond personalized medicine, the emergence of new technologies also generates new trade-offs between humans and society, and between societies and the ecosystems. As mentioned above, the digital revolution is sometimes pictured as an attempt to rationalize resources, and thus it may have emerged as a response to the shortage of resources in the anthropocene (Grumbach and Hamant, 2018). However, it also has many consequences: global digital systems rise a series of new fundamental issues, ranging from cybersecurity to privacy protection, from surveillance to information reliability. If efficiency and safety are clear benefits of algorithmic control, many new questions arise with the advent of the digital society, ranging from global stability to the protection of

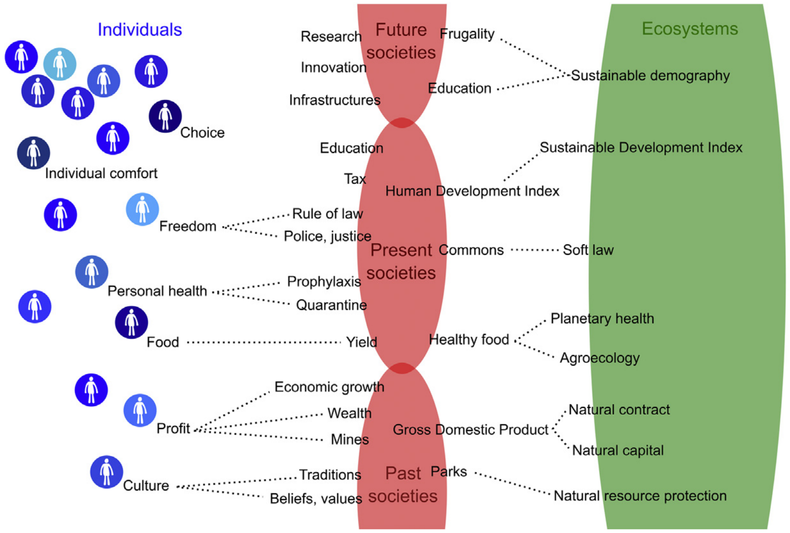

Fig. 4. Tensions between individuals, societies and ecosystems.

individuals. Again, the associated fundamental trade-offs also relate to the general principle of suboptimality, as it has been observed for biological and technological systems at different scales.

In comparison with agriculture, health or language, the digital world might be an ideal subject to analyze the trade-offs associated with suboptimality, simply because its formalization is known and it has emerged in the recent past. While before the digital era, information was under the control of mostly national institutions, such as research centers and traditional media, it is now mainly provided through global digital systems. This raises serious concerns. The first one is related to the weakening of the common cultural grounds on which the public debate can be based, and which include shared values as well as trustable facts. It is also related to the possible isolation of individuals into their digital bubble. Digital systems indeed make full use of personalized recommendations (Ricci et al., 2015), for all interactions with users, whether commercial announcements or search engine results. Optimized to the level of an intimate knowledge of individuals, they might become addictive because of their relevance, but might lack serendipity (Kaminskas and Bridge, 2017).

So far, the digital revolution has favored homogeneity at the top and heterogeneity at the bottom. This trend is promoted by increasingly powerful digital actors, with some regulatory reaction from political powers. Digital players are marginally impacted by hacking, but this could become a more important force in the future. At the same time, it favors a diversity of interactions at the bottom, with an increase of interconnections and their dynamics among actors. Various trade-offs between individual and collective interests are at stake. The balance between global surveillance and the protection of persons is a fundamental example. The increase of surveillance favors homogeneity in the population. The right balance between individual and collective needs has to be found to ensure the diversity required for resilience. The same principle applies to information. The centralisation of its global control favors uniformisation, while the personalization might favor a lack of shared comprehension.

Suboptimality seems to be a well supported way to regulate the trade-offs between individual and society. The examples from this article suggest that beneficial outcomes may arise in the long term from such a strategy, at least in the considered sectors. In the anthropocene, a key challenge for the future will be to assess whether such a paradigm can be applicable at a larger scale, i.e. to regulate the trade-offs between society and the ecosystems. Table 1 lists a number of trends, optimal vs. suboptimal and Fig. 4 presents a succinct presentation of the trade-offs. For instance, concepts like personal health, prophylaxis, and planetary health might very well contradict each other, and impose to balance the interest of individuals and of the ecosystems, as well as between the present and the future. Beyond the collection of solutions to the anthropocene challenges, a major step forward will be to assess: 1) whether suboptimality can indeed provide robustness in the long term to societies and to human-made ecosystems, 2) if yes, to what extent the rising trends in environmental policy (e.g., planetary health, agroecology, commons, soft law,...) are suboptimal, 3) if not, what would be an alternative path to resilience?

7. Conclusion

In essence, this paper questions the sustainability of optimization. Sustainability is often associated with the supposed benefits of personalization and customization, notably through digital innovations. This strategy can generate new attractors, however, and new tensions. Exploring systems belonging to the biosphere or the technosphere, we find that resilience builds on processes that are instead not optimized locally: these systems do not avoid their weaknesses, such as heterogeneity, incoherence, slowness, redundancy, but instead build on them to become adaptable and transformable in the long term. This is suboptimality. Humans are thus bound to question the trade-offs associated with an optimal vs. suboptimal behavior. Examples of transitions to suboptimality in innovations are still rare. Yet, suboptimal transformations are emerging, and take the form of agro-ecology or slow cities for instance. How suboptimal one must be for societies to become resilient is still unclear. Humans will have to define their own boundaries and meet various challenges with possible solutions (Table 1).

Definitions of boundaries to human development already exist, albeit from the Earth standpoint. Building on the Limits of Growth report, planetary boundaries were defined as ”safe operating space for humanity” (Rockstrröm et al., 2009). Humanity may have already overcome three of the nine planetary boundaries, namely climate change, biodiversity reduction and physicochemical deregulation. The associated predictions take different forms, such as ”the revenge of Gaia” (Lovelock, 2007). The idea that a major collapse event could happen within the next decades has gained increasing momentum in many sectors (Diamond, 2005). Yet, this concept may be misinterpreted: ecosystems would be the weak link for human survival; humans would thus need to find ways to fix the Earth boundaries (e.g., through geo-engineering). The formalization of suboptimality echoes the concept of planetary boundaries, but departs from it by taking the human standpoint instead. In that framework, suboptimality would shape a safe operating space for human adaptability and survival, in a fluctuating, unpredictable and uncontrollable environment. In a world currently driven by performance and optimization at all scales and in all sectors, this review suggests that suboptimality may provide an alternative framework to shape more resilient innovations in a rapidly evolving world.

The synthetic argument mainly builds on heterogeneity, which, arguably, best illustrates the trade-offs between individual comfort and global resilience. The collapsed perception of socio-ecosystem complexity is probably best illustrated with Margaret Thatcher's conception that “there is no such thing as society: there are individual men and women, and there are families”. This concept thus reduces the complexity to individuals, while voluntarily ignoring the global interdependencies. Even if the suboptimal path remains to be studied in more depth, one key benefit from this approach is that it forces a multiscale understanding of a problem. Typically, in the anthropocene, where human interactions with Earth systems are still accelerating, a new layer of complexity needs to be incorporated for all choices, the ecosystems. These choices need evaluation with respect to their impact on future generations. Other ways may be possible to capture resilience than suboptimality. Yet, the suboptimal path holds promise toward human-environmental sustainability in the future, with formalization and some proofs of concept from various sectors.

Competing interests

None

Acknowledgments

We thank Pablo Jensen and Sowmya Kadandale for their comments on this manuscript. This work was supported by the European Research Council (ERC-2013-CoG-615739 “MechanoDevo”).

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