Complexity, Entropy production and Industrial ecology

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Summary

Non-equilibrium Thermodynamics leads to the assumption that the entropy production of an ecosystem, designed as a dissipative structure, is in proportion to its complexity. The latter is itself in proportion to the flows of energy, matter and information dispelled by this dissipative structure for maintaining itself in thermodynamical non-equilibrium.
Thus, Industrial ecology is increasingly seen as a vector of productivity intensification of artificial ecosystems, and therefore of complexity. The necessary conclusion is that Industrial ecology, insofar as it complexifies artificial ecosystems, causes increased production of entropy, and therefore reinforces the ecological crisis.

Introduction

Faced with a demand for increasing raw materials and a growing of wastes, the aim now is to decouple economic growth and consumption of natural resources to limit use of raw materials and waste. For achieving this goal, approaches grouped under the expression 'Industrial ecology' are increasinly interesting. The latter today, is designed as an approach whose goal is to create new industrial ecosystems which copy natural ecosystems in which all potential resources are associated with a consumer. This is not the case with modern artificial ecosystems where flows issued from the degradation of resources impact ecosystems until they destabilize them irreversibly.

The idea that waste of ones becomes resources of others is a recurrent theme. The aim of Industrial ecology is to move from a linear economy to a circular economy. It's why, today, Industrial ecology is mainly seen as a process for intensifying the use of primary resources by reusing waste.

The interrogation expressed in this article is that this process is likely to exacerbate the ecological crisis. The reference model that generates this question is the theory of ecosystem designed as a dissipative structure. Some aspects of Ecology and Thermodynamics will feed the discussion on this subject. The proportionality between complexity and entropy production is the basic assumption.

Let's keep in mind Ecology, Thermodynamics, the Theory of complexity, the Ecosystem theory are search fields in full development. Their first results are still controversial. But, there is urgency to participate in the development of new relevant theories to analyze and solve the environmental crisis.

1 The thermodynamical approach of the ecological crisis

Given the difficulties to characterize the contemporary ecological crisis, the need has emerged to have tools to clarify the issues. This theoretical research aims to solve concrete problems. The plight of the city of Naples (Italy) drowned in its waste since the beginning of 2008 shows that the environmental issue is far from being a mystification

Until the second industrial revolution (1945 ->), artefacts were recyclable. Made from natural materials like wood, leather, hemp, etc., their destruction at the end of their life cycle was easy. But today, the new artefacts are not recyclable. Since the 1960's, major biogeochemical cycles are now unable to treat new pollutant emissions. Everywhere, environmental policies are intended to limit the environmental consequences of a socio-economic model which was imposed on the entire planet at the end of the twentieth century.

The combination of thermodynamics and ecology in the systems theory has spawned an original approach of the environmental crisis whose identification of the ecosystem to a dissipative structure is the cornerstone. The origin is in the work of the English ecologist Arthur Tansley to whom is ascribed the authorship of the word 'ecosystem' (1945). Ray Lindemann, in turn, made any living entity as an industrial unit whose productivity is likely to be assessed by a review of " entries ", and" outings "of energy, using notions of thermodynamic previously applied to the thermal systems. Previously, the notion of thermodynamics of living, initiated by Erwin Schrödinger, introduced the idea that living beings minimize locally entropy, whose growth corresponds to death according to the Second principle of thermodynamics. The functions ensuring the local decrease of entropy are grouped under the term metabolism. They correspond to the biological functions of assimilation and elimination of energy. This notion of balance takes up the idea of homeostasis developed by biologists.

Other names participated in this vision. For example, the Americans Eugene and Howard Odum and the Belgian Paul Duvigneaud. The latter conducted its research at the Free University of Brussels. So did, the thermodynamicist Ilya Prigogine. His work on the thermodynamics of non-equilibrium led to the concept of dissipative structure.

Since Ilya Prigogine invented the term, the concept of dissipative structure has become unavoidable to describe the theoretical approaches of ecosystems and the ecological crisis. A dissipative structure is now seen as a system far from thermodynamical equilibrium, separated from the middle by a limit. Its existence is conditional upon the dissipation of energy flows, material and information. This dissipation is a source of production of entropy in accordance with the Second law of thermodynamics.

(1) $dS = dQ/T$

and the equation of the entropic balance:

(2) $dS= d_eS + d_iS \; ; \; d_iS \geq 0$

The reversible entropy (d_eS) is released into the environment. In contrast, the irreversible share (d_iS) remains in the system. The distinguishability between the system and its medium is due to its complexity that is superior.

The approximation of this model designed in Physics and the concept of ecosystem has resulted the designing of the Ecosystem seen as a Dissipative structure.

This invention is issued from a school of thought involving the Environment Department at the University of Paris 7 and the Free University of Brussels. One of the strengths of this association was the European Summer School of the Environment (E4) that took place in Venice in 1976 (Orio, Vigneron, 1976). Paul Duvigneaud and Ilya Prigogine provided a major contribution to the acts of this event (Malaval, 2008).

The ecosystemic function of entropy is the core of the thermodynamic approach of the ecological crisis. This has been possible because non-equilibrium thermodynamics existed. The latter was developed to resolve one of the main paradoxes created by the introduction of the concept of entropy in scientific discourse. How do any organized structures remain despite the Second principle of thermodynamics that condemns them to maximization of the internal entropy and thus to disappear ?

By publishing in 1850 « Abhandlungen über die mecanische Wärme Theorie », Rudolf Clausius (1822-1888) says two cosmogonic conclusions deduced from the First and the Second law of thermodynamics: the Energy of the World is constant ; the Entropy of the world tends to a maximum.

Then, Ludwig Boltzmann (1844-1906) exposed a theory of gases with this same concept of entropy. He gave of it a mechanical vision at the molecular level. He assimilated the concept of entropy to disorder. Consequently, the Second law of thermodynamics became the principle of disorder growth. Here is the origin of this paradox created by the consequences of the Second law of thermodynamics: on the one hand, a growth of irreversible entropy, therefore disorder, and, on the other hand, the realization of the increase of complexity of living structures during the evolution of organisms, ecosystems, etc.

The contribution of Ilya Prigogine was to solve this paradox. He showed that the irreversibility i.e the expression of the growth of entropy in a time perspective, contributes to the emergence of new structures, thus order. These are dissipative structures. The identification of any living system, as a body or an ecosystem, to a dissipative structure is the linchpin of the ecosystemic approach. Stems from this conception the expression of "thermodynamics of living" (Prigogine, 1972).

It is now accepted that, under certain conditions, the evolution of some systems toward order is not contrary to the laws of thermodynamics. All these reflections are based on the equation of the entropic balance (2).

Today, the entropy has become the backbone of the macroscopic study of evolutionary processes in highly complex environments at the molecular level, but also macroscopic systems. This approach combines entropy, stationary state, marginal state, thermodynamical branch, point of bifurcation, production of entropy, and so on.

The ecological crisis is then seen as the consequence of a additional production of entropy. The latter is the result of the dissipation of flows of energy, matter and information (MEI Flows) to maintain the high complexity of our modern artificial ecosystems in thermodynamical non-equilibrium.

This approach is based on proportionality of the dissipation of MEI flows, the complexity of ecosystems and the production of entropy. This additional production of entropy is due to the conversion into useful energy of hidden energies within Techno-science: oil, coal, nuclear energy, gas, etc. What would our Modern world stand without the dissipation of these flows ? This additional production of entropy is the source of the contemporary ecological crisis.

2 Entropy production and complexity

2-a Entropy production

Much of the work of Ilya Prigogine is based on the production of entropy. In 1945, he suggested the Theorem of minimum entropy production that applies to the situations of stationary non-equilibrium. As he said himself, he knew that the minimum entropy production was valid only for the linear branch of irreversible phenomena, the one to which the reciprocity relations of Onsager are applicable. And, thus, his question was: what about the stationary states that are far from equilibrium, for which Onsager relations are not valid, but which are still in the scope of macroscopic description ? (NobelPrice.org, Prigogine). His last reflexions published in his main books allow to develop a theory of the evolution of dissipative structures of any kind. Authors such as Jacques Vigneron (Esquissaud, 1990) have made them working principles of ecosystems. This means that they apply to all systems in thermodynamical non-equilibrium. Under this approach, the biosphere in its entirety is a set of dissipative structures subjected to the same principles of operation. This assertion is deduced from the work of Ilya Prigogine and of his partners.

Therefore, any dissipative structure remains in thermodynamical non-equilibrium because it dispels some flows of energy, matter and information. This situation of thermodynamical non-equilibrium creates the distinguishability between the system and its environment. The system is more structured than its environment. Its entropy is therefore lower than in its environment. As the dissipative system, also, is producing entropy, the differential of entropy between the system and the outside is the consequence of the evacuation of part of this production of entropy out of the system. This phenomenon is formalised by the equation of entropic balance (2) associated with the assumption of local balance. This last phrase means that the system maintains its main state variables at levels that permit its existence through exchanges with the outside world. One example of these state variables is, of course, entropy.

Part of this entropy is released into the environment. It can also be imported from its environment. Its mathematical expression is therefore an undetermined sign (+ or -). That's the reversible entropy: d_eS. The other part cannot be released into the environment. It therefore remains in the system. This is the irreversible entropy: d_iS. Ilya Prigogine showed the importance of irreversibility as a factor of complexification of dissipative systems. The share of irreversible entropy which cannot be evacuated out of the system is therefore increasing over time. This situation is formalized by the Second principle of thermodynamics. This is the source of thermodynamic fluctuations which are depreciated when linear relations dominate inside the system (stationary state).

Otherwise, these fluctuations lead the system toward marginal state where non-linear fluctuations dominate. The result of this situation is the Thermic death (i.e. the system disappears) or the mutation toward a more complex state.

Once this new state has been established, the dissipative structure is more complex. This new non-equilibrium state requires more flows of energy, materials and informations and therefore more entropy is producted. And so on until ...

As Ilya Prigogine wrote (Prigogine, 1989), "The systems which are exporting their entropy are not only increasing the entropy of their environment, they can also undergo some remarkable spontaneous transformations that lead them toward organized states, thanks to the irreversible processes."

This relationship between complexity and entropy production as a prior relationship between complexity and energy flows and ... by extension matter and information. This point was emphasized by ecologists establishing a relationship of proportionality between biodiversity and solar flux. Equatorial ecosystems are more diverse than polar ecosystems. Economists also showed that the level of development of an artificial ecosystem is proportional to the amount of MEI flows they dissipate (WWF, 2006). The geopolitics of energy resources proves our developed societies as modern industrial ecosystems exist because they dissipate these flows.

The level of complexity of a dissipative structure is thus proportional to the quantity of flow allayed. This dissipation is the source of entropy production. There is therefore a relationship of proportionality between the complexity of dissipative system, the quantity of MEI flows dispelled and the production of entropy. Before continuing, we must agree on the concept of polymorphic 'complexity'.

2-b Complexity

The concept of complexity appeared in the late 1970's. These precursors include W. Weaver and Claude Shannon for communication theory, Alan Turing and Heinz von Foerster for theories of computation, Norbert Wiener for cybernetics, David Ruelle for chaos theory, Ilya Prigogine for the thermodynamics of dissipative systems and other, equally important. One of the main lessons from this work is that the order comes from noise (von Foerster) or from entropy (Prigogine), therefore from disorder. One of the main innovations of these new approaches is to reconsider disorder as a fully-fledged phenomenon and to see it as a factor of complexity.

2-b' The complexity categories

This profusion of work is behind many classifications. Among them, there is one of Steven Manson (2001) with his three approaches of complexity:

- The algorithmic complexity combining the theory of algorithmic complexity whose main exponent is Andrei Kolmogorov and Claude Shannon's information theory;
- The determinist complexity combines deterministic chaos theory and the theory of catastrophes. Note that this School has many representatives in France with, among others, David Ruelle and René Thom. These approaches are at the root of a mathematical approach with the concepts of feedback, sensitivity to initial conditions (Butterfly Effect), bifurcations, deterministic chaos, strange attractors and fractal

- S. Manson introduced the notion of 'aggregate complexity'. We suggest the term of 'emergence complexity'. The idea is that a dynamic (synergy) of complexity is developed from the relations between its individual elements. These links are at the origin of complex systems behaviour wich cannot be reduced to that of their parts. For the moment, questions outnumber answers. But, this is a new and very promising field for understanding the working of ecosystems. For the moment, the common factor in these approaches of complexity is that a system is a function of the number of elements and their mutal relations. So, the more complex a system, the higher the number of parts and interactions, and vice versa.

2-b'' Emergence complexity and Energy flows

Despite antagonisms, the need to address the complexity as a phenomenological reality mobilizes more and more researchers in the world. This leads to a vision in which the whole world is a living testimony of an extreme complexity which does not exist for inanimate objects. Such complexity exists at all levels, from the cell nucleus to the complete cell, the individual, the ecosystem, the biosphere. Only the living has varied the opportunities of metabolism requiring the presence of energy produced and sometimes stored. This permits growth and differentiation. One feature of life is being able to capture the flows of resources it needs; energy for example. So, complexity and emergence are consubstantial. This gives some capabilities to mobilize new resources. Complexity is therefore the crucial variable to characterize a system conceived as a dissipative structure.

3 Industrial ecology and complexification

Some other elements of non-equilibrium thermodynamics are to take into account to lead to arrive the idea that the more complex a thermodynamical non-equilibrium system, the more entropy it produces. This hypothesis permits to size up the issues of the ecological crisis in the light of the relationship between the complexity of a structure and entropy production. Thus, there is a link between the complexity of our modern developed societies and the ecological crisis. So, to solve the latter by complexification is a false path. Beyond a certain threshold, capacities of absorption of natural biogeochemical cycles are saturated. Ilya Prigogine himself in the 1970's has initiated this reflection. The question of the consequences of Industrial ecology as a purveyor of intensification of resource use should be put in these terms. If Industrial ecology is a vector of complexification of artificial ecosystems, it reinforces the ecological crisis seen as the consequence of an additional entropy production. And vice versa.

Conclusion

This conclusion comes from a thermodynamic approach concerning the functioning of ecosystems. But this imposes to break new ground because this goes against the tide of the dominant economic model and reinforces the thinking of economists as such Georgescu-Roegen. He was one of the few economists to have integrated the Second principle of thermodynamics in his reflexion. Their thesis is that we must engage in a sustainable decrease to resolve the ecological crisis.

In ecosystemic terms, this means to 'decomplexify' our artificial ecosystems. Nevertheless, this is not what we are doing. ‘Development' is the common ambition everywhere in the world.

This is a recurrent debate between economists and ecologists. To consider a way out of this debate, it is necessary once again to question the validity of the Second law of thermodynamics. Indeed, the thesis outlined in this article is based on the principle that any process of complexification of artificial ecosystems reinforces the ecological crisis because this contributes to increase the production of entropy.

So, this thesis is a direct result of the controversy raised by the consequences of the Second principle of thermodynamics. Once again, it's necessary to question it. Is it valid everywhere ? If it didn’t apply to economic processes, then, it would be possible to 'complexify' any industrial process without additionnal pollution. The debate is far from over. Announcing that the Second principle is false or that it is not valid for living systems would oblige its proselytes to consider other perspectives. But it is necessary for this to get out of the paradigm of Modern science and to reconnect with a philosophical posture. And to conclude with Professor Iosif Tukkel of the Polytechnic University of Saint Petersburg (Russia): "Philosophy always precedes Science."

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