32

Emergy as a Tool for an Integrated Knowledge

Francesco Gonella, Silvio Cristiano, Sofia Spagnolo

ABSTRACT

Starting with Environment Power and Society in 1971, to the Prosperous Way Down proposal thirty years later, most of Howard T. Odum's fundamental titles address explicitly the potential of emergy as a general epistemological tool. But despite the growing number of studies and scholars who use emergy-based analyses, this philosophical potential remains somewhat underestimated and underexplored, however confined within the "emergy community". As a matter of fact, Emergy talks us about deep aspects of the reality as a whole. Concepts like energy quality, donor-side view, as well as principles like the maximum (em)power, open a window to a variety of different disciplines and fields, in the holistic framework of an integrated and "universal" culture. Several emergy scholars have been aware of this need and have worked to export emergetic concepts outside the realm of science. But now the factual inability of decision-makers to take on local and global concerns is urgently demanding for further efforts by the scientific community, aimed at providing tools that are analytically reliable and at the same time able to frame the problems within a systemic, holistic awareness, of which emergy is likely to represent one of the most profound ideas. In this contribution, we first provide a short overview of the epistemological aspects of emergy analysis concepts. Then, we discuss about the potential of emergy as an effective bridge to reconcile different "cultures" within the same integrated picture. Epistemology, Language, Axiomatics are -besides Emergy- some of the virtual keywords of this contribution.

INTRODUCTION

The philosophical aspects of H.T. Odum's work have drawn the attention of several scholars since the very beginning of the Emergy concept development. Titles of his most important and known books (Odum, 1971, 1995, 1996, 2000, 2007) already address explicitly the epistemological content of his theory, pointing out in turn the epistemological values of explaining (theoretical), accounting (analytical) and understanding (epistemic). Words like *modelling*, *scales*, *accounting*, *environment*, *unification*, *society*, and *prosperous* are put together in an epistemologically comprehensive lexicon. Book chapters or sections named for example "Reinforcing structure of religion", "Sins of energy dissipation, autopower", "God and the system" and "Emergy test of morality" (Odum, 1995) further address the capability of Odum to handle, within his theory, issues that appear to be totally separated from the scientific practice. The philosphical content of Odum's legacy has been discussed by several authors, for example in the special issue of the *Ecological Modelling* journal (Vol. 278, 2004), entitled "Philosophical overview of the contributions of H.T. Odum". In order to frame the multi-faceted building of Odum's worldview, it is worth reporting few citations that enlighten very well the conceptual complexity of his cultural contributions, considering that, as a matter of fact, "The contribution (...) given by the theoretical approach proposed by HT Odum is much more than Emergy" (Giampietro, 2000). Maud and Cevolatti (2004) propose one of the few attempts to frame Odum's Energy Systems Language

in a well-defined philosophical approach, by connecting it to the language envisioned by Gottfried Wilhelm von Leibniz (1646–1716) in his *Enlightenment* project, the *Characteristica Universalis*:

> "(...) H.T. Odum and Leibniz have been shown to share the aims of philospophia perennis and the approach of unitas multiplex",

in so intending to point out how Odum's language addresses the existence of a common core of truth (*philospohia perennis*) and most of all the idea of a unity in diversity through purposiveness (*unitas multiplex*). As we will discuss later, these aspects pertain to the core of his philosophical view of the reality, having a place in his personal idea about how the world works. Other Authors have stressed the character of innovation of emergy concepts, a kind of novelty that is not limited to some sort of new technical tool, but on the contrary takes its roots in a new epistemological approach. In this sense, Corrado Giannantoni (2004) talks of a

> "Real and effective introduction of a new concept of Quality to science",

whereas Bernard Patten (1993) had placed side by side the novelty character of the approach and its completeness, stating that

> "Few individuals get to create an entire paradigm in their lifetime. (...) Howard T. Odum is one of those who created his own worldview, and a brand of science to go with it -an entirely new and original system theory of ecology".

In a particularly sharp observation, Tom Abel (2010) addresses the potential of Odum worldview, or paradigm, to cross the disciplinary boundaries of science:

> "Odum's emergy paradigm has arguably given the world an invaluable tool for understanding nature, but also humans, our economy and culture".

In fact, not only Abel refers here to the human society domain, but he also stresses the role of Odum's view as an *invaluable tool for understanding nature*, thus definitely assessing its epistemological foundation, a concept also shared by R.J. King (2004):

> "[H.T.'s work] suddenly gave me a new conceptual framework for understanding how everything tied together. And, I mean everything".

Besides these aspects, epistemic prescriptions have been also pointed out by several further Authors, among whom the most explicit statement probably comes from Charles Hall (2004), who claims for an at least partial re-structuring of our way of approaching the study of systems, underlining the epistemological potential of the maximum empower principle:

> "In my own mind, the search for causality within systems, and the rejection of some existing principles, would be enhanced if researchers would begin with the maximum power principle. It remains surprising to me that this idea has not entered mainstream science".

In our opinion, these words constitute the clear fingerprint of the relevance of the epistemological body of Odum's theory. All the quotations reported above refer to the *philosophical language* used in Odum's systemic approach, talking of things like *paradigm*, *conceptual framework*, *worldview*, *theory*, *principle*, all coming from a lexicon pertaining to that part of general theory of knowledge which deals directly with the foundational nature and with the practice of gaining scientific knowledge, that is, the epistemology. Several papers have been dedicated to the general aspects of Odum's conceptual contributions, for example by Brown and Ulgiati (2004), who investigate both the epistemic features of *quantifying* and *understanding* systems, Ulgiati and Brown (2009), where the relationship between emergy and ecosystems complexity is addressed, Cai et al. (2004), who analyze the maximum (em)power as a foundational principle able to connect man and nature, Bergquist and Rydberg (2008), who explore the transdisciplinary understanding of emergy accumulation, and Hammond (2007), who

places the ideas of Odum in the context of energy and sustainability. Most of these papers present and discuss aspects each one representing *per se* a piece of philosophy, but a framing of all Odum's work within a comprehensive structured epistemology appears to be still lacking.

In this work, some of the main ideas of H.T. Odum legacy are put in the perspective of a modern epistemology by addressing their meaning with respect to different epistemic levels, also considering a future program for the axiomatization of the theory. Framing the theory in a specific school of epistemological thought, like for example Empiricism, Rationalism, Idealism, Constructivism, Foundationalism or so, is well beyond the scope of this contribution, which is not focused in a philosophical academic study. Instead, we aim at exploring the epistemological foundations of Odum's work in the manifold prospect of better *understanding*, *using* and *disseminating* it, hence pursuing the cultural unification program that H.T. Odum himself envisioned throughout all his production, culminating in his prescriptive Prosperous Way Down vision.

EMERGY AND EPISTEMOLOGY

The Emergy concept, along with all the conceptual developments based on it, presents a threefold significance, concerning to 1) the practical value of accounting, 2) the theoretical value or explaining things, and 3) the epistemic value of understanding. These three aspects address the role of Odum's ideas in three fundamental epistemological levels, named after their original German terms:

- *Modell* (model)
- *Weltbild* (image of the World)
- *Weltanschauung* (intuition of the World).

These levels are all present in the practice of getting new scientific knowledge and each one has its own instruments of inquiry, yet with a continuous interaction and exchange between the levels. As a matter of fact, one of the fundamental problems of epistemology in the construction of a scientific theory is the widespread use of tools, meanings and languages belonging to different epistemic levels in the same argumentation. This, as we will se, may give rise to internal misunderstandings and inconsistency of the very meaning of the concepts developed within the theory.

Models, Images and Intuitions of the World

A *Model* is a mental artefact built *ad hoc* to make easier the study of a "piece of nature". One knows a priori that the model is false. It represents an operational tool with practical-heuristic functions, without theoretical valence. It talks about something that does not exist, but it is easy to study, reproducing "sufficiently well" the behavior of what actually exists. Therefore, models have not the theoretical aim of "capturing" the reality, but the practical aim of solving a problem. Various types of models have been classified, for instance, *particularizing models* (e.g., an ideal gas), *substituting models* (e.g., the Newtonian mechanics), *phenomenological models* (e.g., the atmospheric dynamics), *models of objects* (e.g., a rigid body). In the taxonomy of models, a special role is played by the *simulators*, made of a set of algorithms which relate the phase space coordinates of a system with the geometrical space and with the time, such to calculate a trajectory in the phase space. Critics to a model is therefore only pragmatic (to what extent is it useful?). On the other hand, since a theory is falsifiable by the experimental reality, it may become anyway a good model, like in the case of Newtonian gravitation.

A *Weltbild* is set of definitions, axioms and theorems which has the pretension of telling how the reality *is*. It is then true or false, being falsifiable by the experiment, which gives it an epistemic value of truth. Most famous examples are Darwin's evolution theory and Einsteinian gravitation. That of *Weltbilder* is, from a pure scientific point of view, the most important epistemic level, since the images of the world are what we use to call scientific theories. They must be characterized by internal (logical

acceptability) and external (agreement with observations) consistency, giving rise to representations that may allow to *i)* organize in a general, abstract and formal way facts that we already know, *ii)* predict new facts, and *iii)* give knowledge meaning to old and new facts. A *Weltbild* must rely on the scientific method, intended as a set of rules, protocols and conventions based on general criteria of rationality and objectivity which guarantee not only the significance and the communicativeness of the theoretical knowledge acquisition process, but also the reproducibility and the verifiability of the observations which this process is based on.

A *Weltanschauung* is a conceptual construction which gives the reality (the nature) a sense. It contains metaphysical, ethical, aesthetical, ontological principles with which one describes the reality. It is not falsifiable by experience, so in this sense it does not have to do with scientific inquiry, but plays a fundamental role in both the establishment of a theory and in the process of understanding, whatever may be the meaning one could want to attribute to this term. The classical example of that is how different *Weltanschauungen* gave rise to incompatible theories of gravitation. On one hand, Newtonian theory derives from the belief in absolute space and time, coming in turn from the belief in a God creator. On the other hand, Einsteinian mechanics derives from the intuition of a symmetric Universe, whose description must be independent of the point of view, and from the use of a language cleaned up of any anthropocentric element. It is worth stressing that the language played a central role in the building-up of the two theories, and this is a key epistemological aspect for understanding the genesis and the structure of any theory, including Odum's one.

H.T. Odum seems to have been always aware of the risk in mixing up the domains. As sharply observed in Liu et al. (2016),

> "The apparent inconsistency of Emergy-based Sustainability Index with other indicators stems from their different environmental ethics, placed on ecocentrism rather than anthropocentrism".

The inconsistency between different sustainability indicators, intended as technical tools derived from the analytical development of a model, is addressed to depend on different *environmental ethics*. The philosophy at the basis of the interpretation of the indicators is therefore seen as the origin of what is defined as an *apparent* inconsistency. This comment actually evidences a problem that affects various theories, not only in the scientific domain: the debate about formal or technical flaws sometimes hides completely different issues, that have directly to do with the epistemology at the basis of the theories, a baggage which is often taken on board without the necessary critical awareness. The three levels require different attitudes and languages, since a rhetorical and mixed-up use of words and sentences may easily give rise to wrong claims, so the epistemological significance of propositions which are not scientific but are relevant for science should be always made explicit. In this sense, one of the reasons of the widespread scientific illiteracy is likely to come from an unconscious confusion between the above described levels, and even within the scientific community a scarce mastery of the interconnections between linguistic/epistemic levels may lead to totally inconsistent debates, for example, that one concerning the so-called Anthropic Principle.

On the role of language

H.T. Odum's contribution in establishing a new language is one of the most fundamental and recognized features of all his legacy, a fact himself was aware of (Odum, 1995):

> "Because the existing symbolic and mathematical languages were inadequate to represent the thermodynamics of real ecosystems, we invented the energy systems language".

Within any of the three epistemological domains, language in turn works under different levels, of which the most relevant are the

- *Denominative* level
- *Functional* level
- *Communicative* level.

The denominative language names the pieces, objective or abstract, of the systems and of their theoretical structure, as well as the pieces of our knowledge about them. The functional aspects concern with the specific criteria of objectivity for the theory, defining the linguistic forms in which the knowledge is structured. It is important to underline that the functional language allows to organize the hierarchy of the knowledge, and this is even more important where different scales are used in the very definition of the object of the scientific or philosophical inquiry. The communicative language takes the burden of defining suitable analogies and metaphorical tools for an effective communication, even outside the community dealing with the theory. To quote the paper by Grönlund (2008), "Why is emergy so difficult to explain to my environmental science friends?". Communicative language can however unveil hidden isomorphisms between different pieces of knowledge, or different ways of structuring the knowledge itself. And this can be clearly related to the universality of knowledge called for across all the production of Odum, hence once more demonstrating the rigor and the depth of his thought. Communication has been often neglected in the process of establishing a scientific knowledge body, but even besides the social role of science communication to the general public (or at least to the decision-makers), there are two aspects deserving a further comment about the role of communicative language. On one hand, and especially dealing with trans-disciplinary knowledge like that established by Odum, we have to face the problem of what Thomas Kuhn used to call *incommensurability of the languages*, that requires analogical transfers of the linguistic procedures of knowledge structuring through metaphorical mechanisms that allow connections between different languages, what is called *multiple languages pragmatism*. On the other hand, to study a complex system, a boundary must be defined, along with all the interconnections between the different processes which relate the system and its environment. This means that epistemic tools specific of the system must be used along with global linguistic approaches which can point out those interconnections, allowing to export the knowledge outside a specific domain. However, the role of different *narratives* in the process of acquiring and disseminating scientific knowledge, narratives that may pertain to different views of the world, may be quite crucial, as pointed out recently by M. Giampietro and his group (Strand et al., 2016), claiming for the mandatory need of correct narratives of systemic problems.

In the context of languages referred to emergy, diagramming certainly assumes a central role. The power of Odum's diagramming has been developing since his very first papers were published, becoming throughout the decades a quite sophisticated, original and multi-faceted epistemological tool. Odum used diagrams to describe systems in a large variety of contexts and disciplines, and anybody who approaches for the first time his theory cannot avoid to be strongly fascinated by the potential and the originality of this instrument. Mark Brown (2004), in his paper "A picture is worth a thousand words: energy systems language and simulation", summarizes very well the epistemic aspects of emergy diagramming. Let us pay attention to the words he uses:

> "Odum suggested that the first step in simulation modeling should be to draw a diagram of the system. The equations describing relationships and processes of the system then emerge, simply, from the diagram. Thinking on the behavior and structure of a system is done in the diagramming. (...) Odum's energy circuit language is an extremely powerful method for humanity to help the system see and understand itself."

Literature has kept presenting since the emergy birth several studies on the use of energy diagrams to describe systems in different contexts, like for example economics (Abel, 2004; Brown and Ulgiati,

2011) or the study of conflicts (Brown, 1977; Gonella et al., 2017). Indeed, we can affirm that the epistemological tool provided by this diagramming approach is one of the most important and promising aspects in the task of disseminating the "emergy culture". Odum's diagrams are of course linked to the analytical aspects of Emergy algebra, and more in general to the mathematics. In this sense, several studies have been stimulated that propose original developments of the analysis methodology and of its mathematics, among which particularly important are the contributions by Giannantoni (2001) and Tilley (2010). Further approaches are those proposing matrix-based methods (Li et al., 2010), set theory (Bastianoni et al., 2011, Campbell et al., 2013, Morandi et al., 2014) or the use of ternary diagrams (Giannetti et al., 2006).

On the epistemic value of Odum's ideas

The role of Odum's ideas in any of the three epistemological levels described above may be outlined as follows.

Several new concepts are involved in the way H.T. Odum established and developed his *modelling* approach. His contribution, summarized in his book written together with E. Odum "Modeling for All Scales: An Introduction to System Simulation" (2000) is mainly (but not only) traceable in some fundamental elements, that are:

- Emergy diagrams
- Boundary set-up
- Hierarchical levels of analysis
- Multiplicity of scales
- Emergy algebra
- Emergy indicators,

any of which connoting an aspect of Odum's modelling, making the emergy diagramming a quite original approach not only for the practical aim of accounting, but also for a better understanding of the systems dynamics. In this sense, owing to its sophistication, Odum's modelling plays a quite original and important role, since it provides a conceptual feedback to both the other two epistemological levels at the basis of the model construction.

At the *Weltbild* level, the most important contribution (besides the very definition of Emergy) is certainly represented by the Maximum Empower Principle, that even gained the theoretical status of Thermodynamic Priciple (Odum, 1996, 2007). This is also related to the idea of energy quality, at the basis of the hierarchical structure (Brown et al., 2004) that frames the Principle in its operational explanation. With the usual clarity and profoundness, Odum introduced the concept that in the competition among self-organizing processes, network designs that maximize empower will prevail, by reinforcing resource intake at the optimum efficiency. This collects all the elements virtually necessary to frame in a consistent theory the description of how systems work. Odum used to present the Principle explaining its origin, with a sophisticated use of different linguistic approaches at the same time, aimed at developing the basis of a scientific piece of theory in a fully explanatory fashion. In his paper "Energy Systems and the Unification of Sciences" (1995) he uses this approach:

> "But this [thinking in differential equations one piece at a time] approach misses the systems concepts of the network configurations, the design for maximum power, transformities, and emulation. (...) If maximum empower generates certain designs represented by energy-constrained mathematics, then such models will represent any system, even though the mechanisms by which the successful kinetics is reached are different."

Maximum empower has been actually addressed under a variety of points of view, for example by Hall (2004), who discusses some of the main issues related to this topic. From an epistemological point of view, the Principle has the potential to address questions that pertain to our level of understanding the reality, in as much as it represents both a methodological tool and the conceptual key to interpret the systemic operation of virtually any system. As explicitly stated (Odum, 1995),

> "There are universal models of all systems because these are the designs that emerge in self-organization for maximum power. If one can know the energetics and kinetics of a system in advance, even before it exists, one has the principles of planning and management that will be successful. This is a conceptual breakthrough for all fields".

As concerns the level of *Weltanschauung*, the richness of Odum's contribution is ascribable to some pillars of his worldview:

- The donor-side perspective
- Human activity as part of a systemic behavior
- Unity of reality (no isolated systems)
- Unity of science
- Unity of language
- The pulsing paradigm.
-

All of these elements concur in the establishment of Odum's emergy theory, influencing both the theory set-up and its analytical potential, and at the same time being influenced by the knowledge acquired by the practice and the developments in the respective epistemological levels. This fruitful interconnection permeates all of Odum's production, in some sense culminating in the Prosperous Way Down vision (Ulgiati, 2004), that collects and interconnects all these aspects. We can say that H.T. Odum's epistemology and philosophy are not only the conceptual premises of the theory, but at the same time emerge as the "results" of the theory itself.

Any of the elements of Odum's ideas, as expressed above as pertaining to the three epistemological domains, has been defined and discussed in details in the literature, but a comprehensive and ordered taxonomy is still lacking. In particular, in order to better organize Odum's new knowledge, a distinction should be made at least between about independent and derived concepts, pointing out the interconnections between the three semantic domains defined by the epistemic level of the different lexical sets. A clear organization of the pieces of knowledge involved in the emergy concept would allow to *i)* better organize the scientific research, *ii)* better communicate the resutls at any level, and *iii)* better teach the emergy to different audiences. This would also allow to avoid all that critics based on an incorrect understanding of how the concepts and their use are classified. Expressed in a more direct way, this –let us call it– program has clearly to do with classical axiomatization of a theory.

Emergy and Axiomatics

Why Axiomatize? This is the question placed by the philosopher of science Mario Bunge (Bunge, 2017), who says:

> "Axiomatization is uncommon outside mathematics. (...) It concerns not just the formalism, but also the meaning (reference and sense) of the key concepts. (...) Dual axiomatics (...) is not a luxury but a tool helping resolve some scientific controversies".

Axiomatics has been applied so far to very few scientific theories, also for the actual difficulty of putting together sophisticated epistemological knowledge and a comprehensive knowledge of the scientific aspects of a theory. Euclides was the first to do that, and Euclidean geometry is the first axiomatic system. Spinoza and Newton unsuccessfully tried, until David Hilbert developed the concept of abstract theory to proceed with his setting up of the of axiomatization foundations. This allowed to discover the possible existence of isomorphisms between theories, thus providing a powerful tool for any program of scientific inquiry. Besides the technical problems still affecting the emergy analysis, it is evident that the body of knowledge contained in Odum's ideas has all the characteristics to address an effort towards its axiomatization.

A theory may be regarded as a hypothetic-deductive system which proceeds from a set of hypotheses. In order to establish a deductive theory, two set are to be defined:

- A set of expressions, basic (primitive) terms, setting the lexicon of the theory
- A set of statements to be used without questioning their validity, taken as true: the axioms.

To axiomatize will mean to explicit in an ordered way the elements of the two sets, from which all other ideas, called theorems, are produced by purely logical means. An axiomatic system must have some features, namely, formal consistency, independence and deductive completeness of axioms, and completeness and independence of the primary concepts. It is worth stressing that an idea may be important and "central" without being fundamental from a logical-axiomatic point of view. The distinction fundamental/derived is purely logical, depends on the context, but helps to point out the ideas logically stronger, avoiding circularity. For instance, in the classical electromagnetism the fields **E** and **B** (electric and magnetic, respectively) are primitive concepts and Maxwell equations are axioms, whereas the energy conservation (and the very concept of energy!) is derived. But axioms have not an absolute status, since the choice of the set of axioms depends on the framework we want for the theory, which in turn comes to depend on the beliefs at the basis of our intuition of the World. Three kind of axioms may be defined in a scientific theory:

- *Formal* axioms, e.g, "P is a probability measure over a set of elements"
- *Semantic* axioms, e.g, "$P(A, B)$ is the system tendency to pass from A to B"
- *Physical* axioms, for example: "$P(A, B)=P(B, A)$".

Indeed, the fundamentals of Odum's primitive lexicon, as well as the axioms that may be identified within his ideas, mostly concern with general concepts pertaining to systems theory, without needing to include specific elements of specific systems. This means that the descriptive language may then include different, disjoint lexicon sets without losing any epistemic coherence, and this is undoubtedly one important point of his theory. To propose an outline for a possible axiomatization of Odum's work is well beyond the scope of this paper, but it is worth remarking that the seeds of a potentially quite fruitful axiomatization are already for example in the work by Giannantoni (2001), while other Authors pointed out the difficulties in crossing the operational domains of emergy use, for example, Raugei (2011).

SOME CONSIDERATIONS

The legacy of H.T. Odum, after decades of assessments and developments, is more and more extraordinarily prolific and fruitful (Chen et al., 2017), and the conceptual and philosophical aspects carried on by Odum's ideas are still the object of studies under quite different points of view. In this contribution, after a short (and certainly not exhaustive) state-of-the-art of the issue, a path has been outlined for framing the emergy theory within the correct epistemic domains pertaining to such a rich and complex conceptual building. In particular, it is pursued the idea of a possible axiomatization of emergy theory, contributing at the same time to settle some problems that still affect the theory foundations, see for example Brown and Herendeen (1996), and Ortega and Bastianoni (2014), and to

establish a more effective structure aimed at disseminating and teaching Odum's ideas. As Odum himself pointed out (1995),

> "Once a systems perspective is introduced, then most students can readily see its application and the failures of approaches that are not systems oriented".

On the other hand, he also remarked how the difficulty of doing that is not only methodological, but unfortunately it has to do with a cultural mainstream that is being even worsening in its approach to problems like the global sustainability (Ortega, 2012), and the capacity of the societies to face threats that are going to become irreversible tragedies. In his own words (Odum, 1995):

> "This leaves the universities with a special responsibility to do the new and long-range development that ultimately take back from government the scientific leadership. (...) In many cases, the duty of universities to do long-range, original science is hindered by chairpersons and deans pressuring the young to seek available money, any money, rather than striking out in original directions".

H.T. Odum provided all of us with suitable epistemological tools for describing, accounting, and understanding the reality, and the hope is that the "emergy community" urgently finds better and better ways to pursue his thought, by an intellectual path that, starting from the systems complexity, through the self-organization provided by feedback networks, defines the holistic features that *govern* the systems we are part of and we are surrounded by.

REFERENCES

Abel, T., 2004. Systems diagrams for visualizing macroeconomics. Ecological Modelling 178: 189–194.

Abel, T., 2010. Human transformities in a global hierarchy: Emergy and scale in the production of people and culture. Ecological Modelling 221: 2112–2117.

Bastianoni, S., Morandi, F., Flaminio, T., Pulselli, R.M., Tiezzi, E.B.P., 2011. Emergy and emergy algebra explained by means of ingenuous set theory. Ecological Modelling 222: 2903–2907.

Bergquist, D., Rydberg, T., 2008. Towards A Transdisciplinary Understanding of Emergy Accumulation. In: Proceedings from the 5th Biennial Emergy Conference, Gainesville, Florida, pp. 15–22, https://cep.ees.ufl.edu/emergy/conferences/ERC05_2008/proceedings.shtml.

Brown, M.T., 1977. War, Peace and the Computer: Simulation of Disordering and Ordering Energies in South Vietnam. In: C.A.S. Hall and J.W. Day, Jr. (Eds.), Ecosystem Modeling in Theory and Practice: An Introduction with Case Histories, Wiley, pp. 394–417.

Brown, M.T., Herendeen, R.A., 1996. Embodied energy analysis and EMERGY analysis: a comparative view. Ecological Economics 19: 219–235.

Brown, M.T., 2004. A picture is worth a thousand words: energy systems language and simulation. Ecological Modelling 178: 83–100.

Brown, M.T., Odum, H.T., Jorgensen, S.E., 2004. Energy hierarchy and transformity in the universe, Ecological Modelling 178: 17–28.

Brown, M.T., Ulgiati, S., 2004. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. Ecological Modelling 178: 201–213.

Brown, M.T., Ulgiati, S., 2011. Understanding the global economic crisis: A biophysical perspective. Ecological Modelling 223: 4–13.

Bunge, M., 2017. Why Axiomatize? Found. Sci. 22: 695–707.

Cai, T.T., Olsen, T.W., Campbell, D.E., 2004. Maximum (em)power: a foundational principle linking man and nature. Ecological Modelling 178: 115–119.
Campbell, D.E., Pulselli, R.M., Bastianoni, S., Morandi, F., 2013. Using the language of sets to describe nested systems in emergy evaluations. Ecological Modelling 265: 85–98.
Chen, W., Liu, W., Geng, Y., Brown, M.T., Gao, C., Wu, R., 2017. Recent progress on emergy research: A bibliometric analysis. Renewable and Sustainable Energy Reviews 73: 1051–1060.
Giampietro, M., 2000. All I wanted to say about emergy analysis in the last 20 years and I was never able to say (unpublished).
Giannantoni, C., 2001. Mathematical Formulation of the Maximum Em-Power Principle. In: Proceedings from the 2nd Biennial Emergy Conference, Gainesville, Florida, p. 2-1 to 2-19, https://cep.ees.ufl.edu/emergy/conferences/ERC02_2001/proceedings.shtml.
Giannantoni, C., 2004. A harmonious dissonance, Ecological Modelling 178: 263–265.
Giannetti, B.F., Barrella, F.A., Almeida, C.M.V.B., 2006. A combined tool for environmental scientists and decision makers: ternary diagrams and emergy accounting. Journal of Cleaner Production 14: 201–210.
Gonella, F., Elia, C., Cristiano, S., Spagnolo, S., Vignarca, F., 2017. From Head to Head: An Emergy Analysis of a War Rifle Bullet. Peace Economics, Peace Science and Public Policy 20170004.
Grönlund, E., 2008. Why Is Emergy So Difficult to Explain to My Environmental Science Friends? In: Proceedings from the 5th Biennial Emergy Conference, Gainesville, Florida, 33–39, https://cep.ees.ufl.edu/emergy/conferences/ERC05_2008/proceedings.shtml.
Hall, C.A.S., 2004. The continuing importance of maximum power. Ecological Modelling 178: 107–113.
Hammond, G.P., 2007. Energy and sustainability in a complex world: Reflections on the ideas of Howard T. Odum. Int. J. Energy Res. 31: 1105–1130.
King, R.J., 2004. Creating a new conceptual framework: environment power and society. Ecological Modelling 178: 159–162.
Li, L., Lu, H., Campbell, D.E., Ren, H., 2010. Emergy algebra: Improving matrix methods for calculating transformities. Ecological Modelling 221: 411–422.
Liu, X., Liu, G., Yang, Z., Chen, B., Ulgiati, S., 2016. Comparing national environmental and economic performances through emergy sustainability indicators: Moving environmental ethics beyond anthropocentrism toward ecocentrism. Renewable and Sustainable Energy Reviews 58: 1532–1542.
Maud, S., Cevolatti, D., 2004. Realising the Enlightenment: H.T. Odum's Energy Systems Language qua G.W.v Leibniz's Characteristica Universalis. Ecological Modelling 178: 279–292.
Morandi, F., Campbell, D.E., Bastianoni, S., 2014. Set theory applied to uniquely define the inputs to territorial systemsin emergy analyses. Ecological Modelling 271: 149–157.
Odum, H.T., 1971. Environment, Power and Society, Wiley, New York.
Odum, H.T., 1995. Energy Systems and the Unification of Sciences, in: C.A.S. Hall (Ed.), Maximum Power: The Ideas and Applications of H.T. Odum. Colorado University Press, Boulder CO, pp. 365–373.
Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making, Wiley, New York.
Odum, H.T., Odum, E.C., 2000. Modeling for All Scales: an Introduction to System Simulation, Academic Press, San Diego.
Odum, H.T., Odum, E.C., 2006. The prosperous way down, Energy 31: 21–32.
Odum, H.T., 2007. Environment, Power and Society for the Twenty-first Century: the Hierarchy of Energy, Columbia University Press, New York.
Ortega, E., Bastianoni, S., 2014. Open Issues in Emergy Methodology. In: Proceedings from the 8th Biennial Emergy Conference, Gainesville, Florida, 297-308, https://cep.ees.ufl.edu/emergy/conferences/ERC08_2014/proceedings.shtml.

Ortega, E., 2012. Critical Analysis of Green Economy Proposals. In: Proceedings from the 7th Biennial Emergy Conference, Gainesville, Florida, pp. 51–60, https://cep.ees.ufl.edu/emergy/conferences/ERC07_2012/proceedings.shtml.

Patten, B.C., 1993. Toward a More Holistic Ecology, and Science: The Contribution of H.T. Odum, Oecologia, 93:, 597-602.

M. Raugei, 2011. Emergy indicators applied tohumaneconomic systems –A word of caution. Ecological Modelling 222: 3821–3822.

Strand, R., Saltelli, A., Giampietro, M., Rommetveit, K., Funtowicz, S., 2016. New narratives for innovation, Journal of Cleaner Production, in press.

Tilley, D.R., 2010. Mathematical Revisions to Odum's Dynamic Emergy Accounting, Proceedings from the 6th Biennial Emergy Conference, Gainesville, Florida, pp. 583–597, https://cep.ees.ufl.edu/emergy/conferences/ERC06_2010/proceedings.shtml.

Ulgiati, S., 2004. H.T. Odum and E.C. Odum, the prosperous way down. Ecological Modelling 178: 247–250.

Ulgiati, S., Brown, M.T., 2009. Emergy and ecosystem complexity, Communications in Nonlinear Science and Numerical Simulation 14: 310–321.