Cybergization of Modern Social-Economic Systems

Accounting for Changes in Metabolic Identity

Ansel Renner, A. H. Louie, and Mario Giampietro

Abstract In Part 1 of this paper, the metabolic nature of social-economic systems is explored. A general understanding relating the various constituent components of social-economic systems in a relational network is presented and used to posit that social-economic systems are metabolic-repair (M, R) systems of the type explored in relational biology. It is argued that, through modernization and globalization, social-economic systems are losing certain functional entailment relations and their ability to control replication. It is further argued that modern social-economic systems are losing control over their identity. In Part 2, the implications of those realizations are explored in terms of effective accounting methodology and a practical set of methods capable of harnessing the deep complexity of social-economic systems. In terms of methods, a practical set of metrics defined through the lenses of a macroscope, a mesoscope, and a microscope is presented. Intended to be used simultaneously, the various descriptive domains suggested by our three scopes may be useful for decision-makers who wish to make responsible decisions concerning the control of system identity change or to combat processes of societal cyborgization.

Keywords Metabolism · Social-economic system · Relational biology · Thermodynamics

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1 Part 1

This manuscript's first part aims to establish bridges between concepts used in different disciplines. Firstly, we reflect on and apply the epistemological tools used in the multidisciplinary field of societal metabolism. We then also reflect on and apply the explanatory resources and rigorous definitions provided by the field of relational biology insofar as they are useful in the classification of social-economic systems as living (and therefore "authentically", not simply "metaphorically", metabolic) or non-living. The discussion made in Part 1 sets up Part 2's presentation of three scopes useful for the practical assessment of social-economic systems.

Before setting off, it is productive to position our discussion of metabolic systems in relation to the broader discussion of complex systems. Following the classification and nomenclature used in relational biology, the set of living systems (**O**) is a subset of the set of complex systems (**I**). Furthermore, the set of complex systems is a subset of the set of natural systems (**N**). In other words, $\mathbf{O} \subset \mathbf{I} \subset \mathbf{N}$. The union of the set of complex systems (**I**) and the set of simple systems (**S**) is the set of natural systems (**N**). In other words, $\mathbf{S} \cup \mathbf{I} = \mathbf{N}$. *All metabolic-repair (M, R) systems are complex systems and all replicative (M, R)-systems are living systems.* Refer to Louie [1] for detailed causal definitions of each of the system types referred to.

1.1 Societal Metabolism

As originally noted in the field of physical biology, i.e. the work of Lotka [2], metabolic processes may be meaningfully divided into an endosomatic class and an exosomatic class. Endosomatic metabolism refers to processes taking place *within* a given organism insofar that an organism uses fluxes of negative entropy available in the environment to sustain a process of exergy degradation[1] and stabilize their metabolic pattern while reproducing, maintaining, and adapting their structural and functional elements. An exosomatic process refers to a situation in which the processes of exergy degradation used to stabilize a metabolic pattern take place *outside* a given organism. This essential distinction between types of metabolic process also applies in the domain of social-economic systems [4]. In that context, for example, it is advantageous to differentiate between an endosomatic population (e.g. the population of humans) and an exosomatic "population" (e.g. the population of machines) [5]. Post-Industrial Revolution, the exosomatic population has been seen to dramatically increase in both absolute and relative terms [6]. This is a change in metabolic identity that cannot be ignored—we will come back to it in Sects. 1.4 and 1.5.

In his discussion of the biophysical nature of the economy, Georgescu-Roegen [4] made a further critical distinction in his flow-fund model. In a metabolic pattern,

[1] Use of available energy forms that can be converted into useful work according to the characteristics of the user and the environment within which the conversion takes place [3].

flow elements are those that do not maintain their identity over the course of an analysis. Food or exosomatic energy inputs that are consumed during the course of an analysis certainly do not maintain their identity—they are examples of flow elements. Fund elements are those that do maintain their identity during the course of an analysis. Over the timespan of a week, an organism typically maintains its identity, assuming it consumes an acceptable flow of food and exosomatic energy inputs—it is an example of a fund element. Stocks are not the same as fund elements. If a deposit or withdrawal is made to or from a stock, the stock does not maintain its identity.

So, flows, funds, and stocks can be used as descriptive categories when describing endosomatic and exosomatic metabolic processes and populations. This is a good first step in the assessment of social-economic systems as metabolic systems. What we lack, however, is an explanatory framework allowing us to answer questions of "why?" with assertions of causality. The division between negative and positive forms of entropy in non-equilibrium thermodynamics is semantic—it is contingent on the identification of "whys?" in relation to metabolic processes. Section 1.2 introduces a language of causality which allows us to develop substantive (transferable) theories about metabolic processes.

1.2 Explanatory Resources (Causality)

Relational biology is a discipline concerned with the elaboration and assessment of causal relations (mappings) useful for the derivation of meaningful answers about a system. It is the operational inverse of reductionist biology. While reductionist biology begins an analysis by throwing away function (keeping matter), relational biology begins an analysis by throwing away matter (keeping function). See Rashevsky [7, 8] for its origins, Rosen [9, 10] for its most well-known presentation, and Louie [1, 11, 12] for its most recent advances.

The causal building blocks considered by relational biologists are the four Aristotelean causes. Each of the four causes may be considered as an irreducible explanatory resource, essential to answer an inquiry of "why?". For Aristotle, and indeed in relational biology, all four causes must be identified in a complete explanation. An elaboration of anything less is a partial description.

- *Material cause* is that out of which something is constituted. For example, the concrete and steel that constitute the roads and buildings of a modern city could be identified as a material cause.
- *Formal cause* is the "blueprint" or "form" of something, or the "account of what it is to be". For example, the layout/configuration of a city could be identified as a formal cause.
- *Efficient cause* is the primary agent of change realizing or initiating something which is done. For example, the construction workers who erected the roads and buildings of a city could be identified as an efficient cause.

- *Final cause* is the sake for which something is done, i.e. to what end? Two examples that could be identified as the final cause of a city are the desire to live closer to other humans and the desire to shelter oneself from the unpredictable nature of the non-constructed environment.

Before moving any further, a disclaimer is merited concerning final cause. Although final cause and teleology are frequently considered to be synonyms, there is an important clarification that can be made. Final cause is teleological to the extent it references an end purpose, but it is not psychologized in the sense there is no notion of intention when a final cause is formally mapped. This point is further discussed in another paper of this issue [13]. In contrast to formal mappings of final cause, teleology typically implies the existence of intentionality [9, 14]. Even the necrophiliac[2] mode of science known as reductionism does not, on a theoretical basis, disallow the practical use of formal mappings of final cause.

1.3 Relational Characterization of a Societal Node

In social-economic systems, Aristotelean causality can be intuitively applied at a low-level scale in the description of social practices. Bundles of social practices can, in turn, be used as building-block descriptions of societal sectors—the nodes of a relational description of a social-economic system. At a very basic level, social practices describe the convergence and linkage between meanings, competences, and materials, as expressed by a group of agents [16]. Meanings are characterizable as final causes, competences as formal causes, materials as material causes, and expressing agents as efficient causes. Figure 1 and the discussion that follows illustrate a consideration of these explanatory resources in relation to a generic conceptualization of an agriculture sector—an entity that emerges from a bundling of the expression of social practices related to agriculture.

The right-hand side of Fig. 1 explores the final causes of agriculture—the set of behaviors expected from it. In this sense, the right-hand side details the array of end-uses (a "hologram") of agriculture and considers the agriculture sector as a social-economic component. The left-hand side of Fig. 1 explores the various material, formal, and efficient causes of agriculture. In this sense, the left-hand side of Fig. 1 refers to the agriculture sector as a social-economic constituent. Used in contrast to component, the term constituent refers to a structural definition. In material terms, the agriculture sector is made up of various vegetal and animal organisms and products, machinery, buildings, infrastructure, and so forth, in which human activity is used to control the processes of exergy transformation. Its formal cause is the configuration of such material considerations, including, for example, the relative break-down and

[2]"Necrophilia in the characterological sense can be described as *the passionate attraction to all that is dead, decayed, putrid, sickly; it is the passion to transform that which is alive into something unalive; to destroy for the sake of destruction; the exclusive interest in all that is purely mechanical. It is the passion 'to tear apart living structures*'" [15].

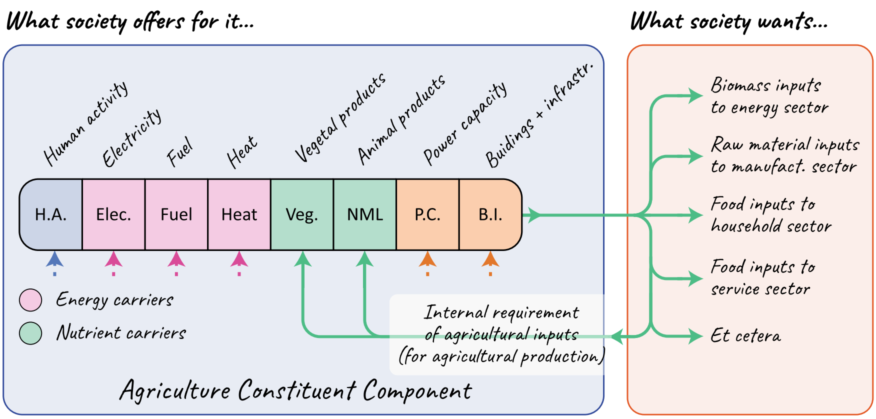

Fig. 1 Biophysical demand placed by a social-economic system on its constituent component "agriculture"

arrangement of materials. Lastly, an account of human activity controlling the power capacity provided by machines is a proxy consideration of the efficient cause of social practices of agriculture—the proximate "agents" behind the realization of the agriculture sector (see [17]).

Keeping in mind the language presented in Sect. 1.1, the ratio comparison between the use of an exosomatic population of funds (such as machines, buildings, and infrastructure) and the use of an endosomatic population of funds (humans) can provide a characterization of the degree of capitalization of an agriculture sector. A similar comparison between flows can provide further contextual information such as the degree of reliance on external inputs—expected relations that must be guaranteed.

1.4 Society as a Relational Network

We now wield the tools needed to represent social-economic systems as metabolic networks in which constituent components stabilize each other in an impredicative (self-referential) set of relations. Such a representation allows for the generation of characteristics such as the relative size of constituent components, their expected metabolic rates, and, more in general, a definition of societal identity.

Societal sectors, such as the agriculture constituent component depicted in Fig. 1, are distinguishable elements of social-economic systems that generate an emergent property. Each sector has a meaningful and relevant identity regarding an identity-dependent coupling of positive and negative forms of entropy. Each of the sectors of a social-economic system can also be said to have a final cause. Historically, a dialectical exchange of functional entailment (a mapping where the final cause of one process becomes the efficient cause of another, also referable to as hierarchical composition) was made between the various sectors of social-economic systems. In the modern world, a world prevailed over by biophysically affluent urbanities, the mapping of functional entailment has become predominantly unidirectional between some sectors.

The social-economic system presented in Fig. 2 represents an archetypical modern social-economic system. It is divided between dissipative sectors (sectors involved in the metabolism of biophysical flows and use of exosomatic devices, without producing either of them) on the top and hypercyclic sectors (sectors which output more biophysical flows and/or exosomatic devices than they use for their own metabolism and repair) on the bottom. N.B. The distinction between dissipative and hypercyclic processes was proposed by Ulanowicz [18] in his analogous study of the organization of ecological metabolic networks. If the purpose of social-economic systems is understood to purely be the reproduction of the endosomatic population at a desirable level of metabolic dissipation, then the set of dissipative sectors can also be understood as anabolic and the set of hypercyclic sectors as catabolic.

In modern societies, the final causes of dissipative sectors map to the efficient causes of each other and to the various hypercyclic sectors of the economy. The dissipative sectors provide a system of control for the hypercyclic sectors. The final cause of the hypercyclic sectors, on the other hand, is more and more to provide exosomatic flows of biophysical material to dissipative sectors—no questions asked. This role of the hypercyclic sectors was not always the case—this role was not the case in pre-industrial agrarian societies, for example [6].

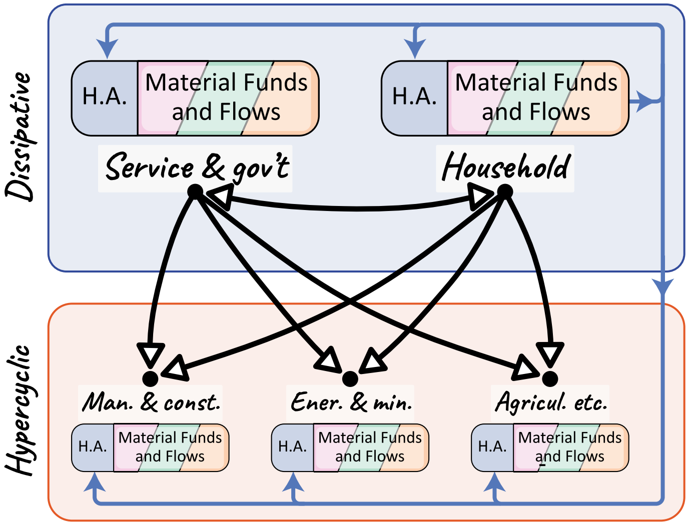

Fig. 2 Functional entailment between the components of a social-economic system (hollow-headed black arrows) and its vector of control (solid-headed blue arrows) with sector details: (i) household; (ii) service and government; (iii) manufacturing and construction; (iv) energy and mining; and (v) agriculture, forestry, and fishing

1. In the *service and government sector*, an effective interface between production and final consumption is made. The preservation, notional reproduction, and adaptation of institutions occurs. Trust, one prerequisite for proper market operations, is generated. Regulations are made. Education, security, and law enforcement are enacted.
2. In the *household sector*, humans as individual or family-level agents are reproduced and maintained. Social practices and normative values are shaped. Market preferences are shaped and voting and political participation occurs.

Together, the two dissipative sectors identified in Fig. 2 provide a reflexive analysis of a social-economic system's identity, feelings, emergent concerns, and interactions with the external world (due to the presence of humans). Contingent analysis, required to establish societal priorities in an impredicative option space, is made. Likewise, analyses required for the tackling of the unavoidable existence of uncertainty and the unavoidable existence of legitimate but contrasting perspectives are made.

However, functional entailment, shown in Fig. 2 as running between the dissipative sectors and from the dissipative sectors to the hypercyclic sectors, can only be defined after matching a definition of "metabolic demand", coming from a specific metabolic pattern of system components, with a definition of "metabolic supply", coming from a specific metabolic pattern of system components. Functional entailment represents a top-down constraint (directly resulting in "downward causation") related to an emergent property (an "identity"). Material entailment (a mapping where the final cause of one process becomes the material cause of another), on the other hand, relates to the need for establishing coherent biophysical relations. In this sense, material entailment represents a bottom-up constraint (indirectly resulting in so-called "upward causation"). Material entailment is about establishing a feasible and viable state-pressure relation with various local admissible environments. In the language of non-equilibrium thermodynamics, it can be represented by the definition of a local coupling of patterns of exergy degradation (state) mapping onto fluxes of negative entropy (pressure) across different levels. Figure 3 presents a different view of our archetypical modern social-economic system. Figure 3, supplementary

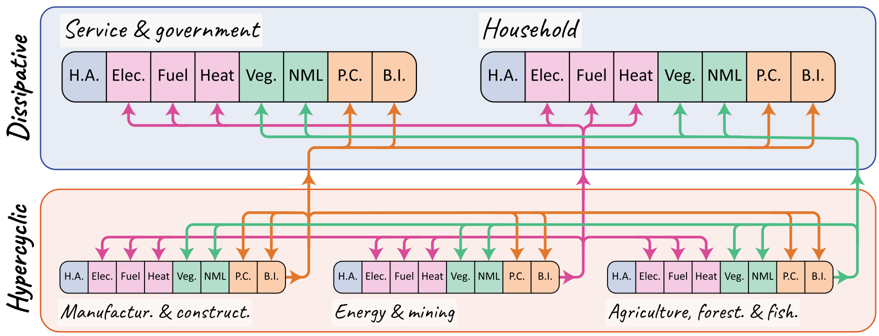

Fig. 3 Material entailment between the constituents of a social-economic system

to Fig. 2, highlights relations of material entailment. It should be clear that the hypercyclic sectors, in their provisioning of material flows to dissipative sectors, present a biophysical constraint on each other and on the dissipative sectors.

1.5 Society as an (M, R)-System

There is a theorem in the field of relational biology which states that all living systems are formalizable as *replicative* metabolic-repair (M, R) systems. Let's dig deeper. In terms of the concept of metabolism, we've already established a respectable understanding. Repair, on the other hand, is the reproduction of a catalyst of change. In terms of causal mappings, functional entailment is repair and material entailment is metabolism. Lastly, replication is not "self-replication" in the modern biological sense. Rather, the output of replication in (M, R)-systems is repair (see [1, 19, 20]). A similar concept is found in the bioeconomics of Georgescu-Roegen—the economy does not produce goods and services but rather reproduces the fund elements producing and consuming goods and services to guarantee adaptability and a desirable state [21].

If the functional entailment relations presented in Fig. 2 were a complete graph[3]—as could easily be claimed to have been the case in pre-modern society—then we would consider social-economic systems to be in a situation of deadlock. Deadlock, the relational analog of impredicativity (that great hallmark of complexity), is a "situation wherein competing actions are waiting for one another to finish, and thus none ever does" [1] (p. 208). Under a state of deadlock, with all mappings of final causality locked up in hierarchical composition, a social-economic system could be said to be *closed to efficient causation.* To apply Georgescu-Roegen's flow-fund concept, the social-economic system could be said to be in a situation where all metabolic funds internally generate each other, given the presence of favorable boundary conditions. In that circumstance, a social-economic system could be referred to as living under the same causal foundation that conventional biological organisms are said to be living.

1.6 Externalization and Cyborgization

In addition to the interactions presented in Figs. 2 and 3, social-economic systems interact with their context in at least two essential ways. Firstly, they interact with the local biosphere. Secondly, they interact with other social-economic systems, e.g. through trade.

[3]Since our mappings are directed, we refer here to a complete directed graph, meaning that every pair of vertices (contextually, societal sectors) is connected by a pair of unique edges (contextually, functional entailments)—one in each direction.

The first type of interaction implies a change in consideration from social-economic systems to social-ecological systems. A social-ecological system can be defined as a complex of constituent components that operates within a prescribed boundary and is controlled in an integrated manner by activities expressed both by a given set of social actors and institutions operating in the economy (under human control, in the technosphere) and a given set of ecosystems (outside human control, in the biosphere). This change in consideration from economic to ecological involves a description of an entropically favorable state-pressure relation between a symbiotic technosphere and biosphere.

For the second type of interaction, we will focus on the externalization of economic processes through trade. Through imports, a social-economic system is able to reduce its requirement to secure a reliable internal flow of biophysical material—a flow that would otherwise need to be produced by its own hypercyclic sectors. In this sense, externalization increases the ability of a system to free itself from the need to establish a complete set of internal relations of material entailment. It reduces the constraints determined by the counterfactual local pressures of downward and upward causation.

However, from a relational perspective, externalization also has a dark side. Externalization may be seen as a major reason why many modern social-economic systems are losing their control over the reproduction, maintenance, and adaptation of their own identity. Through processes of modernization (and changes in considerations of desirability, related to rising expected levels of material standard of living), the ability of dissipative sectors to provide feedback through functional entailment relations with hypercyclic sectors—to "cast their vote"—has been seen to systematically reduce. As a result, social-economic systems are losing their ability to replicate[4] and losing control over their ability to repair. In essence, they are losing control over their identity. The many benefits of modernization may be seen to have come hand-in-hand with a local breaking of the closure to efficient causation of social-economic systems—a process of "cyborgization" of society in which societal identity is being increasingly determined by external factors.

As Swyngedouw [22] points out, cities are exemplars of this process of cyborgization of society. N.B. Cities also epitomize externalization in social-economic systems. A cyborg is a hybrid between an organism and at least one artificial component, where an artificial component is a simple system tasked with restoring an organic function. From the relational biology perspective, a human (a type of organism) equipped with and reliant on a pacemaker (a type of artificial component) is already a cyborg, albeit a very basic cyborg. With no great stretch of the imagination, we can similarly conceptualize cities as extensive mechanical cocoons that offer a wide array of inert goods and services as replacements of societal functions. It is undeniable that cities have many desirable characteristics, but it is also undeniable that they are the technocratic havens of social agents operating, as Turkle [23] phrased it, "alone together". As previously mentioned, the unorthodox economist Georgescu-Roegen was clear in identifying that the final cause of the economy is not "to produce goods

[4]"Replication" not in the molecular biology sense, rather in the relational biology sense described at the head of Sect. 1.5.

and services" but rather to reproduce fund elements associated with the production and consumption of goods and services. That is, the final cause of the economy is simply the reproduction of itself while guaranteeing an "enjoyment of life" to citizens. Considering Georgescu-Roegen's understanding of the economy, it would be advisable for social-economic systems to make a careful assessment of their intrinsic, complex network of functional and material entailments before making the societal decision to off-shore, or replace with artificial components, their societal organs. An organism turned cyborg can no longer decide how it wishes to enjoy life.

2 Part 2

The functional entailment from the dissipative sectors of a social-economic system to the hypercyclic sectors, as shown in Fig. 2, represents a set of powerful initial constraints on the definition of that system's option space (downward causation). Conversely, the potential combinations of material, formal, and efficient causes in the hypercyclic sectors of society can either expand or—more likely—limit the initial option space definition (so-called "upward causation"). In this sense, the option spaces of social-economic systems are constrained by a double contingency (downward and upward causation). A second paper in this same volume explores in greater detail the ideas of downward and upward causation in relation to the generation of meaning and identity preservation in complex adaptive systems [13]. What will instead be outlined in what remains of this paper is a set of quantitative accounting considerations capable of informing processes of societal deliberation over questions such as: Assuming a given social-economic system, to what degree is change in identity to be allowed? In what ways should identity change be considered permissible?

By applying the concepts outlined in Part 1, it is possible to distinguish which entailment relations are necessary (which isn't to say sufficient) for the maintenance of the various aspects of a social-economic identity. In that endeavor—the maintenance of a social-economic identity—it is advisable to use at least three lenses. In the following sub-sections, we propose a macroscope, a mesoscope, and a microscope. N.B. As also claimed by the principle of biological relativity [24, 25], no one scope is "better" than the other. The adoption of a specific scope must follow the societal selection of a question or concern. Generally, all three scopes should be used simultaneously (Fig. 4).

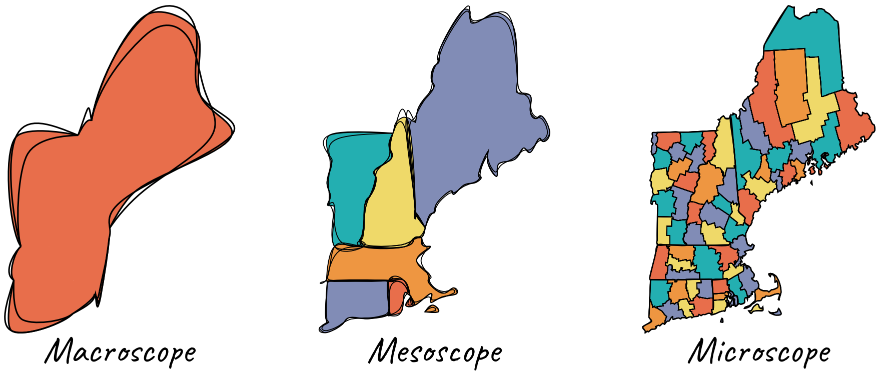

Fig. 4 Three lenses useful for the relational characterization of a social-economic system and its option space. No single lens is superior

2.1 Macroscope

A macroscope is a highly approximated descriptive domain—the result of liberal coarse-graining. When looking through a macroscope, one sees a profile of end-uses and an approximated vision of the results of functional entailment in a social-economic system (the set of final causes is associated with the set of end-uses). A profile of allocation of fund and flow elements by constituent component (sector) is defined both in terms of the relative size of aggregate-level funds and the specific metabolic rates of those funds.

In using a coarse characterization of metabolized flows ("Metric #1"), it is possible to characterize an array of end-uses in terms of: (i) a set of final causes in a dendrogram of splits of fund element across different levels of organization; (ii) a definition of the various exosomatic metabolic rates of those funds (like a neural-network integrating the dendrograms of splits of funds with dendrograms of splits of flows); and (iii) a calculation of a "bio-economic pressure" determined by the relative size and relative endosomatic and exosomatic metabolic rates of the various constituent components of society [26].

2.2 Mesoscope

A mesoscope shows an approximated vision of the relations of the various supply systems of a social-economic system as it interacts with the local biosphere and other external social-ecological systems. The mesoscope maps the requirement of metabolized flows—as characterized in an array of end-uses defined using the macroscope's Metric #1—against a non-equivalent characterization of the supply of flows required to stabilize the metabolic pattern. The metabolized flows expressed using Metric #1 are thereby converted into commodity flows measured using another metric ("Metric #2").

For example, a given quantity of megajoules of liquid fuels (Metric #1) characterized against a given mix of liters of gasoline, diesel, or kerosene (Metric #2). Alternatively, a given quantity of kilocalories of vegetal food (Metric #1) characterized against a given mix of kilograms of grains, vegetables, or fruits (Metric #2). The adoption of Metric #1 allows the identification of a final cause for supply systems—functional complexes capable of expressing an integrated set of efficient causes matching a given final cause. In this way, the metabolic pattern described by an array of end-uses is translated into a given requirement of supply systems capable of providing the supply, described using Metric #2. At this point, concerning the level of openness of a system, we can identify: (i) the fraction of the metabolized flows generated by local supply systems operating inside the border of a social-economic system; and (ii) the fraction the metabolized flows generated by "virtual supply" systems operating outside the border of a social-economic system. This is indeed an important piece of information since it characterizes, when considering material entailments, the degree of freedom from internal constraints on the societal option space. In conclusion, supplementing Metric #1's characterization of the metabolic pattern with Metric #2 allows the identification of the required set of efficient causes (either expressed locally or embodied in imported commodities) determined by the definition of final causes expressed by human funds. Since no information is given about "how" these efficient causes are expressed (no mention of material or formal cause), the relation between Metric #1 and Metric #2 can be considered a *downward causation* of metabolic pattern determination.

2.3 Microscope

Use of a microscope descriptive domain yields an approximated vision of the relations of the mix of various structurally defined production processes—defined as combinations of material, formal, and efficient causes—into functional units, which express functions required at the mesoscope level. Using a microscope, it is possible to assess the technical viability, environmental pressures, and environmental impacts (feasibility) of production and consumption processes.

For each of the "supply systems" defined using the mesoscope and represented in quantitative and qualitative terms using Metric #2, it is possible to generate a non-equivalent quantitative characterization of the mix of the processes needed to generate that supply system. That is, at a lower level of analysis, we can describe the specific combination of material, formal, and efficient cause (the local end-uses, or local social practices) that, when combined in a functional bundle, are capable of expressing the functions associated with given supply systems. The quantitative representation of these relations requires the adoption of a third metric (Metric #3) in which we describe the combinations of fund elements and flow elements (end-uses) in local production processes. In this way, for example, a commodity flow such as a quantity of kilowatt-hours of electricity can be mapped onto a mix of quantities of electricity generated by different types of power plants (funds and flows mixed together in the analysis). It's worthwhile to elaborate with examples: (i) baseload electricity can be produced using either nuclear power plants (fund) using uranium (flow) as part of the material cause or coal power plants (fund) using coal (flow) as part of the material cause; (ii) peak electricity can be produced using either hydropower plants (fund) using falling water (flow) as part of the material cause or gas turbines (fund) using natural gas (flow) as part of the material cause; and (iii) intermittent electricity can be produced using either wind turbines (fund) using the kinetic energy of the wind (flow) as part of the material cause or photovoltaic cells (fund) using solar radiation (flow) as part of the material cause. Of course, the material needed to construct the power plants (exosomatic funds) should also be included in the analysis, whenever relevant. The various combinations of lower-level elements associated with a specific combination of material, formal, and efficient cause within a given specific production process can be characterized using an array of vectors—a *metabolic processor* in relational analysis—and stored in a database. Each specific combination maps onto an expected profile of inputs and outputs that can be combined into a chained functional unit (a sequential pathway, for example, the extraction of coal, transportation of coal, and production of electricity in a power plant) for which it becomes possible to calculate the metabolic pattern.

3 Conclusion

In this contribution, we used the well-established language of relational biology to present an initial exploration of social-economic systems as replicative (M, R)-systems. We concluded that social-economic systems are metabolic in a causal sense identical to the that of biological organisms. Shortly after arriving at that conclusion, we declared that modern society is undergoing a process that could be understood as a *cyborgization*—a process by which society is progressively losing control over the definition of its own identity. Though we identified several ways in which the process of cyborgization is creating a fragile society, we made no mention of whether the process itself is "good" or "bad". Nevertheless, substantial desirability concerns arise from the process of cyborgization of society—those concerns can be understood as "good" or "bad" once framed by a specific stakeholder and in the light of a specific question or concern.

Governance in complexity is about staying on the horns of dilemmas. While it is possible to put a harness on complexity, it is impossible to tame complexity. To put a harness on social-economic systems understood as complex systems, we suggested the simultaneous use of a macroscope, a mesoscope, and a microscope to observe different relevant aspects of societal performance. The use of our three scopes allows for the establishment of a bridge between representations of the metabolic pattern of social-economic systems from the perspectives of: (i) downward causation—what is required in terms of supply systems by the characteristics of societal metabolism as observed with the macroscope; (ii) upward causation—what can be supplied by local combinations of microscope production processes given the constraints provided by the characteristics of formal causes (technical viability, i.e. internal constraints, determined by technical coefficients) and material causes (environmental feasibility, i.e. external constraints, determined by biophysical processes outside human control); and (iii) the role that externalization through trade plays in lessening the constraints imposed by upward causation (characterized using the mesoscope).

The general approach to the assessment of social-ecological systems in this contribution has been developed within the auspices of the European project *Moving Towards Adaptive Governance in Complexity* [27]. Initial examples of applications of macroscopic views of social-economic systems are available in [26, 28–30], of mesoscopic views in [31, 32], and of microscopic views in [33, 34]. Substantial work remains in terms of exploring the many implications of relational biology for the assessment of societal metabolism and in further formalizing the approach.

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References

1. Louie, A.H.: More Than Life Itself: A Synthetic Continuation in Relational Biology. Ontos Verlag (2009)
2. Lotka, A.J.: Elements of Physical Biology. Williams & Wilkins Company (1925)
3. Gaudreau, K., Fraser, R.A., Murphy, S.: The tenuous use of exergy as a measure of resource value or waste impact. Sustainability **1**, 1444–1463 (2009). https://doi.org/10.3390/su1041444
4. Georgescu-Roegen, N.: The Entropy Law and the Economic Process. Harvard University Press, Cambridge, MA (1971)
5. Mayumi, K.T.: Sustainable Energy and Economics in an Aging Population: Lessons from Japan. Springer (2020)
6. Giampietro, M.: Multi-scale Integrated Analysis of Agroecosystems. CRC Press LLC, New York (2004)
7. Rashevsky, N.: Mathematical biophysics. Nature **135**, 528–530 (1935). https://doi.org/10.1038/135528a0
8. Rashevsky, N.: Organismic sets: outline of a general theory of biological and social organisms. Bull. Math. Biophys. **29**, 139–152 (1967). https://doi.org/10.1007/BF02476967
9. Rosen, R.: Life Itself: A Comprehensive Inquiry Into the Nature, Origin, and Fabrication of Life. Columbia University Press, New York (2005)
10. Rosen, R.: Essays on Life Itself. Columbia University Press, New York (2000)

11. Louie, A.H.: The Reflection of Life: Functional Entailment and Imminence in Relational Biology. Springer, New York, NY (2013). https://doi.org/10.1007/978-14614-6928-5
12. Louie, A.H.: Intangible Life: Functorial Connections in Relational Biology. Springer International, Cham, Switzerland (2017). https://doi.org/10.1007/978-3-319-65409-6
13. Giampietro, M., Renner, A.: The Generation of Meaning and Preservation of Identity in Complex Adaptive Systems: The LIPHE4 Criteria. In: Braha, D. (ed.) Unifying Themes in Complex Systems X. Springer, Cham, Switzerland (2021)
14. Chase, M.: Teleology and final causation in Aristotle and in contemporary science. Dialogue Can. Philos. Assoc. **50**, 511–536 (2011). https://doi.org/10.1017/S0012217311000527
15. Fromm, E.: The Anatomy of Human Destructiveness. Holt, Rinehart and Winston, New York (1973)
16. Shove, E., Pantzar, M., Watson, M.: The Dynamics of Social Practice: Everyday Life and How It Changes. SAGE Publications Ltd., London (2012)
17. Patching, D.: Practical Soft Systems Analysis. Pearson Education Limited, Essex (1990)
18. Ulanowicz, R.E.: Growth and Development: Ecosystems Phenomenology. Springer, New York (1986)
19. Rosen, R.: A relational theory of biological systems. Bull. Math. Biophys. **20**, 245–260 (1958). https://doi.org/10.1007/BF02478302
20. Rosen, R.: A relational theory of biological systems II. Bull. Math. Biophys. **21**, 109–128 (1959). https://doi.org/10.1007/BF02476354
21. Giampietro, M., Pastore, G.: Biophysical roots of 'enjoyment of life' according to Georgescu-Roegen's bioeconomic paradigm. In: Mayumi, K., Gowdy, J. (eds.) Bioeconomics and Sustainability: Essays in Honor of Nicholas Georgescu-Roegen, p. 438. Edward Elgar Publishing (1999)
22. Swyngedouw, E.: Circulations and metabolisms: (hybrid) natures and (cyborg) cities. Sci. Cult. (Lond) **15**, 105–121 (2006). https://doi.org/10.1080/09505430600707970
23. Turkle, S.: Alone Together: Why We Expect More from Technology and Less from Each Other. Basic Books, New York, NY, USA (2012)
24. Noble, D.: A theory of biological relativity: no privileged level of causation. Interface Focus **2**, 55–64 (2012). https://doi.org/10.1098/rsfs.2011.0067
25. Noble, R., Tasaki, K., Noble, P.J., Noble, D.: Biological relativity requires circular causality but not symmetry of causation: so, where, what and when are the boundaries? Front. Physiol. **10**, 1–12 (2019). https://doi.org/10.3389/fphys.2019.00827
26. Giampietro, M., Mayumi, K., Sorman, A.H.: The Metabolic Pattern of Societies: Where Economists Fall Short. Routledge, London (2012)
27. Giampietro, M., Aria, M., Cabello, V., Cadillo-Benalcazar, J.J., D'Ambrosio, A., de La Fuente, A., Di Felice, L., Iorio, C., Kovacic, Z., Krol, M.S., Madrid López, C., Matthews, K., Miller, D., Musicki Savic, A., Pandolfo, G., Peñate, B., Renner, A., Ripa, M., Ripoll Bosch, R., Serrano-Tovar, T., Siciliano, R., Staiano, M., Velasco, R.: Report on Nexus Security Using Quantitative Story-Telling. http://magic-nexus.eu/sites/default/files/files_documents_repository/magic-ga689669-d4.1-revision.pdf
28. Velasco-Fernández, R., Chen, L., Pérez-Sánchez, L., Giampietro, M.: Multi-scale integrated comparison of the metabolic pattern of EU28 and China in time. EUFORIE Project. Deliverable 4.4. ICTA, Autonomous University of Barcelona. ICTA, UAB (2018). http://www.euforie-h2020.eu
29. Pérez-Sánchez, L., Giampietro, M., Velasco-Fernández, R., Ripa, M.: Characterizing the metabolic pattern of urban systems using MuSIASEM: the case of Barcelona. Energy Policy. **124**, 13–22 (2019). https://doi.org/10.1016/J.ENPOL.2018.09.028
30. Giampietro, M., Saltelli, A.: Footprints to nowhere. Ecol. Indic. **46**, 610–621 (2014). https://doi.org/10.1016/j.ecolind.2014.01.030
31. Cadillo-Benalcazar, J.J., Renner, A., Giampietro, M.: An accounting framework for the biophysical profiling of the European agricultural system. In: ALTER-Net and EKLIPSE (eds.) The EU Biodiversity Strategy Beyond 2020: Research Insights and Needs for Biodiversity and Ecosystem Services in Europe. Ghent, Belgium (2019)

32. Renner, A., Cadillo-Benalcazar, J.J., Benini, L., Giampietro, M.: Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. Ecosyst. Serv. **46** (2020). https://doi.org/10.1016/j.ecoser.2020.101195
33. Cabello, V., Renner, A., Giampietro, M.: Relational analysis of the resource nexus in arid land crop production. Adv. Water Resour. **130**, 258–269 (2019). https://doi.org/10.1016/j.advwatres.2019.06.014
34. Di Felice, L.J., Ripa, M., Giampietro, M.: An alternative to market-oriented energy models: nexus patterns across hierarchical levels. Energy Policy **126**, 431–443 (2019). https://doi.org/10.1016/j.enpol.2018.11.002