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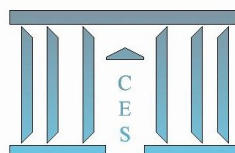
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**From Methodology to Practice (and Back):
Georgescu-Roegen's Philosophy of Economics
and the Flow-Fund Model**

Quentin COUX

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From Methodology to Practice (and Back): Georgescu-Roegen's Philosophy of Economics and the Flow-Fund Model

Quentin Couix*

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Abstract

Despite Georgescu-Roegen's important contribution to mathematical economics, his later methodological criticism of models has received little attention from economic philosophy. This paper fills this gap first by examining his explicit methodology and connect it with the literature. Building on the distinction between dialectical and arithmomorphic concepts, I characterise his approach to theory-making as a three steps process of idealisation, isolation and arithmetisation. In this framework, models perform two functions, checking for logical consistency and facilitating understanding, which can be related to the idea of modelling as theorising.

I then confront these principles with Georgescu-Roegen's flow-fund model of production. His methodology serves as a reading grid of the theory, which in turn reveals limits and complementary principles. Idealisation provides conceptual foundations, isolation delimits relevant problems, and structural consistency is rigorously followed, while the two functions of models are illustrated by the derivation of older principles and the understanding of organisational patterns of production. But different functions appear as the model also enables to check for conceptual consistency and the understanding it provides contributes to the formation of new concepts. Hence, the consistency and complementarity between Georgescu-Roegen's methodology and practice of theory-making provide a useful background for further investigations of his thought.

Key words: Georgescu-Roegen, methodology, philosophy, models, flow-fund, production function, input-output, substitution.

JEL classification : B16, B31, B41, C02, C65, D24, E23, O10.

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Introduction

In one of his latests essays, reflecting on his academic life, Nicholas Georgescu-Roegen remarked that his “epistemological addiction” had led him to the conclusion that if “one starts only with mathematics, one is likely [...] to be trapped inside it” (1992). This claim, and many other similar ones in his work, have often been understood as a radical opposition to the modelling practices that became wide spread in economics in the second half of the 20th century. However, such an interpretation would miss two points. First, it overlooks the importance of the word “only” in this statement. In fact, Georgescu-Roegen’s writings show a constant preoccupation of adopting a balanced position, that neither abandons models nor rely exclusively on them. Second, even after he explicitly started this reflection on models in the mid 1960s, himself continued to build his own representation of production, known as the “flow-fund model”. However, the relation between these two aspects, the general reflection on mathematical models and his representation of production, are not always very clear in his own work, and have not been studied in details. Accordingly, the present paper pursues two goals: to offer a comprehensive account of his thought on modelling, and to confront it with the construction of his model of production.

This investigation is made particularly interesting by the specific position of Georgescu-Roegen in the history of economic thought. To start with, he has been both an eminent participant of the rise of mathematical tools in economics. Conventionally, the first signs of this movement that transformed the discipline are identified in the 1930s, in institutions such as the Cowles Commission and the Econometric Society, and around two distinct practices: econometric models and mathematical economics (Morgan and Knuuttila, 2012). As a matter of facts, this is exactly the period at which Georgescu-Roegen came to the US, after completing a Ph.D. in statistics at the Sorbonne in France on the cyclical components of time series. He could therefore have enrolled in research in econometrics, but the end of the Harvard Economic Barometer program, for which he had obtained a scholarship, decided otherwise. Instead, his meeting with Joseph Schumpeter introduced him to economic theory and he became mainly interested into mathematical economics, even though later he published some essays on statistics.

Quickly, he made some important contributions to the emerging literature intending to formalise rigorously the neoclassical theory, in particular regarding the problem of integrability in his 1936 paper on “The Pure Theory of Consumer’s Behaviour” (Zamagni, 1999; Lenfant, 2012). This opened him a promising career with a proposition to join the economics faculty at Harvard and the project of a treatise on theoretical economics with Schumpeter, which he dismissed to return to his native country, Romania (Georgescu-Roegen, 1992). However, when the country fell under the communist regime, he had to flee for political reasons, and was back in the US in July 1948. It then didn’t take him much time to get back into the community of mathematical economists thanks to his temporary position in Wassily Leontief’s Harvard Economic Project and his participation to the Cowles Commission 1949 Conference on “Activity Analysis of Production and Allocation”, which retrospectively appeared as a central event for the introduction of new mathematical

techniques in economics (Düppe and Weintraub, 2014).

However, his critical look regarding the orientation of the discipline, which is already perceptible in his first contributions, became more and more obvious. For instance, he suggested that the fixity of preference was an inadequate feature of the theory of consumer behaviour and proposed to take into account hysteresis in their evolution (Georgescu-Roegen, 1950). This was not only a re-examination of some postulate of the theory, as in the case of the integrability problem, but a more radical proposition of reorientation (Hands, 2006). Later on, he was at the center of the publication of the Arrow-Debreu model of General Equilibrium, since, as associate editor of *Econometrica*, he was in charge of the referee process of their paper. As he received two contradictory answers, his own positive position was crucial in the acceptance of the paper, but it was accompanied by a set of seventeen remarks that “more or less set the stage for many of the issues that would be subsequently involved in methodological discussions of what has come to be called the Arrow-Debreu model” (Weintraub and Gayer, 2001, p. 435). He later developed some of his criticisms of the model, in particular those related to distribution, in a paper called “Economic Theory and Agrarian Economics” (1960), which he interpreted afterwards as the beginning of his marginalisation (Georgescu-Roegen, 1992).

But the divorce became obvious in the introduction he wrote for *Analytical Economics* in 1966a, a recollection of his most important articles until then. This introduction was in fact the first step toward his major book *The Entropy Law and the Economic Process* in 1971 which exposes in the most detailed way his criticism of neoclassical economics, and shows that it rests on methodological considerations. Indeed, the book is a broad investigation into the philosophy of science in general and the philosophy of economics in particular, on which he relies to expose his own approach. In a way, this is not so surprising in the history of economic thought, where, from the 19th century up until the late 1970s, the philosophy of economics is elaborated by practitioners and does not yet constitute a separate field of inquiry (Mäki, 2012a). But Georgescu-Roegen’s book certainly constitutes one of the most ambitious contributions in this respect at the time, mixing references from philosophy, mathematics, physics and economics. In a sense, this only reflects the ambitious aims it implicitly pursues: to give solid foundations to his earlier criticisms and to reorient the course of the discipline accordingly.

Clearly the latter goal was not achieved, as his book was only influential in a limited area of the discipline and was not discussed by the most prominent economists at the time. But more strangely, this contribution didn’t get much attention either from the specialised field of economic philosophy and methodology, that took shape at the end of the 1970s. Among the few influences, Philip Mirowski’s work on the relations between mechanics and neoclassical theory, as a vehicle for the introduction of mathematical formalism in economics, constitutes one of the most developed investigations of one of Georgescu-Roegen’s insights (Mirowski, 1989). But beyond this, we find practically no mention of his work in the main journals and books on economic methodology. Historians of economic thought in turn have been more directly interested in Georgescu-Roegen’s theoretical switch, which necessarily requires reference to his economic philosophy. This is especially the case for articles

that deal with the importance of evolution in Georgescu-Roegen's shift, in relation with Schumpeter's own perspective (Bobulescu, 2012; Heinzl, 2013) or his traditional association with "degrowth" (Missemer, 2016). However, on this side either we can't find a comprehensive and critical account of his conception of the role of mathematical models in economic theory, which, therefore, constitutes the first purpose of the present paper.

Moreover, while the observation above concerned the general methodological claims of Georgescu-Roegen on models, it is also true of his actual practice of modelling. In particular, there is no detailed account of the flow-fund model, which constitutes his most developed analytical contribution after the 1970s. In ecological economics, where Georgescu-Roegen's influence has been most important, the focus has been on issues related to thermodynamics. General presentations of his work (Beard and Lozada, 1999; Missemer, 2013) dedicate only a few pages to present the elementary aspects of the flow-fund model, and the situation is similar in investigations of his role in the emergence of ecological economics (Røpke, 2004; Ould Boye, 2014). If we turn toward more formal and less historically minded presentations, we encounter two distinct lines of research. The first one investigated further the relevance of Georgescu-Roegen's framework to analyse the organisation of production processes at the micro level (Morrone, 1992; Scazzieri, 1993; Marzetti, 2013). The second one is more concerned with the analysis of the global interdependence of production processes and the comparison with alternative theories such as Sraffa's model (Mayumi, 1999; Kurz and Salvadori, 2003). However, in both cases, the formal outlook and the restricted spectrum of interest do not enable to examine the global relevance of Georgescu-Roegen's analysis of production and its relation to his methodology. This constitutes the second aim of the present paper.

More precisely, the two aims stated above are interwoven: I intend to learn about the practice from methodology, and to learn about the methodology from the practice. In fact, this reciprocal relation relies on two slightly different conceptions of methodology. In the first case, I refer to the *explicit* methodology of modelling as it permeates in Georgescu-Roegen's general philosophy of economics. In the second case, I refer to the *implicit* methodology that appears to lead his investigation of the flow-fund theory of production. In order for the issue not to seem useless, it is important to underline that the relation between both does not appear clearly. In fact, the structures of the methodology and the model are not themselves transparent, and therefore, it is only by a reconstruction of both that we can achieve our purpose.

To do so, it seems relevant to start with the reconstruction of Georgescu-Roegen's explicit methodology, which is mainly contained in *The Entropy Law and the Economic Process*. However, we should also rely on the relevant literature in economic philosophy, in which two subjects seem particularly interesting to put Georgescu-Roegen's approach into perspective. The first one concerns the issue of realism in economic theory (Lawson, 1999; Hausman, 2000; Mäki, 2012b). Building on how the problem is tackled in general philosophy of science and the recurrent controversies it has triggered in economic thought, this literature enables to characterise more accurately Georgescu-Roegen's own position. The second topic of interest is that of

models. In this respect, the literature has evolved from a focus on the definition and structure of models (da Costa and French, 2000; Chao, 2009) to an approach more interested in the functions of models in economic practices (Morgan, 2008; Morgan and Knuuttila, 2012). In the case of Georgescu-Roegen, both aspects appear relevant to apprehend his conception of the roles of models in economics¹. This is what is done in section 1.

Second 2 in turn confronts the interpretation of Georgescu-Roegen's philosophy with the structure of his theory of production. This means that, on the one hand, it relies on the explicit methodology to make sense of the process by which the flow-fund model is built. In this sense, it functions as a reading grid that enables to reconstruct the structure of the theory which is only implicit in Georgescu-Roegen's exposition. On the other hand, this process of theory-making gives the opportunity to learn more about his methodology through the practice, showing the obstacles it faces, clarifying ambiguities, and revealing additional principles that were not spelled out explicitly. To do so, I mainly rely on the extensive presentation of the model in *The Entropy Law and the Economic Process*, but I also occasionally refer to some of his other contributions on the subject when they provide additional insights (Georgescu-Roegen, 1969b, 1970, 1976).

1 Georgescu-Roegen's philosophy of economics

As underlined above, the philosophical foundations of Georgescu-Roegen's approach to economics are mainly presented in *The Entropy Law and the Economic Process*. However, the book is a broad investigation in many issues of the philosophy of science, from those related to measurement in physics and economics, to those concerned with evolution in life and social sciences, passing by the opposition between mechanics and thermodynamics. Therefore, it is necessary to select what is interesting to understand his methodology of economics, and in particular the role of mathematical models, aspects which are mainly discussed in chapters II, III and XI. Since they are dispersed in different parts of the book, it is useful to highlight the main features of his philosophy of economics and relate them to each other in order to assess the global consistency of his approach. This leads to a "critical" exposition of his methodology, in the sense that it puts it in perspective with conventional issues in economic methodology, which enables to characterise it better and underline its specific features.

¹In this context, "theory" should be understood as the conceptual structure of the paradigm, the intellectual framework through which economists conceive their object of study. Concepts can be expressed through definitions and illustrations, and they can be articulated together to form propositions. The whole conceptual structure is expressed in literary language. Therefore, we consider "models" separately from theory, as purely mathematical systems and the graphical representations they can provide. Finally, "methodology", both explicit and implicit, denotes the relations between theories and models.

1.1 Arithmomorphism and dialectics

To begin with, one of the most important aspects of Georgescu-Roegen's philosophy of economics is his distinction between "arithmomorphic" and "dialectical" concepts². On the one hand, concepts that can be defined very accurately are called arithmomorphic because "any particular real number constitutes the most elementary example of a discretely distinct concept" (1971, p. 44). By this, Georgescu-Roegen means that, even though we speak of the "continuum" of real numbers, each number does not overlap with any other, which is true not only for symbols but also for the concepts they support. Moreover, he argues that this property of discrete distinction is the essence of logic, because it can deal only with propositions that have an unequivocal meaning.

On the other hand, dialectical concepts "are surrounded by a penumbra within which they overlap with their opposites" (1971, p. 44). As an illustration, Georgescu-Roegen suggests that "life" in natural sciences belongs to this category, because "there are some crystal-viruses that constitute a penumbra between living and dead matter". In economics in turn, he claims that the concept of "want" pertains to the same category because "any particular want [...] imperceptibly slides into other wants". As a result, he considers that "the dialectical spectrum of human wants [...] has long since been covered under the colorless numerical concept of 'utility' for which, moreover, nobody has yet been able to provide an actual procedure of measurement" (1971, p. 52). In both cases, the laws of logic don't apply to these concepts because they do not abide by the principle of contradiction that "B cannot be both A and non-A" (1971, p. 46)³.

In order to clarify what this distinction, Georgescu-Roegen discusses the issue of how we relate concepts to elements of the real world in both cases. According to him, the difficulty of deciding if a particular quadrangle is a "square" or not is linked to the imperfection of the measuring instruments. Hence, the number of elements that can be considered as such may be restrained if the precision of the instruments increases, but the concept itself is perfectly well defined. Conversely, the problem of determining whether a particular country is a democracy or not is linked to the inherent imprecision of the concept, which is itself due to the imperfection of the mind.

Another important detail regarding dialectical concepts is that, even though they overlap with their opposite, they are distinct from their opposite. Therefore, in a certain range we can easily determine what corresponds to the concept and what does not. Relying on the example of "life" again, Georgescu-Roegen asserts that "in most cases we can decide whether a thing [...] represents a living organism or

²Georgescu-Roegen elaborates this distinction by discussing ideas from philosophers, such as Plato, Aristotle, Hegel, Bergson or Whitehead, and philosophically inclined scientists such as Poincaré, Borel, De Broglie, Russel or Bridgman. My point here is not to analyse exhaustively this discussion and the exact relation of his philosophy to these many influences, but rather to outline the general principles of this philosophy and compare it with some of the questions raised by contemporary philosophy of economics.

³Georgescu-Roegen adds that "even though the line followed by the present argument is inspired by Hegel's logic, it does not follow Hegel in all respects" (1971, p. 46, n. 27). However, he doesn't go further in explaining the difference between the two.

lifeless matter” (1971, p. 47). Precisely, the “dialectical penumbra” is located at the frontier between the concept and its opposite.

But, while this penumbra is the source of the difficulty to deal with dialectical concepts, for Georgescu-Roegen, it is also the only way to apprehend qualitative change. Indeed, he suggests that qualitative change is a continuous evolution of social and natural entities that imperceptibly leads to radically new one. Stated in another way, qualitative change is not a movement along successive discretely distinct states, be they continuous like the real numbers, and instead happens inside the penumbra surrounding the frontier of dialectical concepts. As a consequence, “qualitative change eludes arithmomorphic schematization” (1971, p. 63), and this is one of the reasons for his dissatisfaction with the conventional definition of economics as the study of how given means allow to achieve given ends. According to him, this hides the most important aspect of the economic process, namely the qualitative change of the available means and the desirable ends, which he describes as “a continuous spectrum of forms which slide into each other as the economic process evolves and ultimately become as different as a bird is from a worm” (1971, p. 330).

At bottom, the issue is related to our ability to identify “sameness” between different entities and between entities at different times, which negatively defines qualitative change as “not being the same”. In this regard, Georgescu-Roegen adopts a subjectivist point of view, insisting on the role of the mind as an instrument of observation:

The upshot is that we have to recognize once and for all that sameness is an internal affair of a single mind, whether an individual one or one embracing several individual minds. We have gone too far, it appears, in believing that natural phenomena can be reduced to signal registrations alone and hence that mind has no direct role in the process of observation. Mind, on the contrary, is as indispensable an instrument of observation as any physical contrivance. The point is of paramount importance for social sciences, and I shall return to it later on. (Georgescu-Roegen, 1971, p. 75)

This perspective echoes the contemporary “realist” approach of Mäki (2012b), in the sense that it considers economics as a science of “commonsensibles”, of which we have a more or less direct experience and understanding. This approach underlines that the process by which this is achieved involves “concepts and inference, cultural meanings and shared interpretations”, what Mäki summarises as “the unavoidable hermeneutic moment of economics” (2012b, p. 8-9). Georgescu-Roegen in turn adopts the perspective of Blaise Pascal who distinguished “two distinct qualities of our intellect: *esprit geometrique* and *esprit de finesse*” (1971, p. 52, italics in the original). Even though Georgescu-Roegen never uses the latter, “*esprit de finesse*” and hermeneutics seem tightly connected here, both conveying the idea of a subjective interpretation of concepts progressively made more accurate. A task which is proper to the mind and never really ends because of the dialectical nature of the concepts involved in this process ⁴.

⁴It is on this ground that Georgescu-Roegen criticises logical positivism for “proclaiming that

For the same reason, Georgescu-Roegen argues that dialectical reasoning cannot be *exact*, but can be correct. And he adds that there are “two known methods for testing the correctness of dialectical reasoning: Socratic analysis and analytical simile” (1971, p. 337). Focusing on the latter, which denotes the kind of models used in mathematical economics, he suggested two merits: “bringing to light important errors in the works of literary economists who reasoned dialectically”; and “illustrating certain points of a dialectical argument in order to make them more understandable”. Hence, according to this view, the role of mathematical models in economics is to examine the logical consistency of an argument and to facilitate understanding.

However, Georgescu-Roegen denies that such a model can provide a tool to test the validity of the theory as a representation of reality. According to him, in physics, this is made possible by measuring instruments that provide an objective standard of accuracy for the model. But he claims that in social sciences, “there is no such objective standard of accuracy” (1971, p. 333). This is presented as an argument against the instrumentalist epistemology traditionally associated with Milton Friedman (1953), which suggests that the validity of the theory should rest on the accuracy of its predictions as measured by empirical tests. The point is also intimately linked to Georgescu-Roegen’s criticism of the relevance of statistical tests in economics, which he summarises using the metaphor that “one can always prove that inside any log there is a beautiful Madonna” (1971, p. 333)⁵. The main consequence of this discrepancy regarding the status of models in physics and in economics is that in the former they can serve as “blueprints” or “guides to automatic action”, whereas in the latter they are only “simile” that must be considered as guides for economic policy with “delicacy and sensitivity of touch” (1971, p. 333).

Therefore, Georgescu-Roegen’s considerations on the role of models in economics connects in many ways with the contemporary literature on modelling practices, as presented for instance in Morgan (2008). In particular, this literature suggests three epistemic functions of models, respectively labelled as “fitting theories to the world”, “modelling as theorising” and “investigative instruments”⁶. Accordingly, the first

whatever the purpose and uses of dialectical concepts, these concepts are antagonistic to science”. He argues in particular that such a claim present a fundamental contradiction, since it cannot itself do without dialectical concepts. On the other hand, he doesn’t side with a radical hegelian perspective, “maintaining that knowledge is attained only with the aid of dialectical notions” (1971, p. 50). But he admits that most hegelians have acknowledged the usefulness of the more rigorous arithmomorphic concepts, and himself endorses this middle position.

⁵Even though he was first trained as a statistician, Georgescu-Roegen did little work on this topic once he turned to economics, and rather focused on theoretical matters. He nevertheless published a few reflections on the status of econometrics, where he developed his ideas regarding its limited relevance as an empirical test (Koopmans et al., 1952; Georgescu-Roegen, 1966b, 1967).

⁶Morgan and Knuuttila (2012) present three other labels of epistemic functions: “experimental exploration”, “conceptual exploration” and “inferences from models”. These correspond to a different way of categorising modelling practices. In fact, each one of the new categories partially overlap with the old ones, for instance “experimental exploration” shares aspects with both fitting data to the world and investigative instruments. This shows that the items of each categorisation themselves overlap in many respects, and that the categorising principles are not unique and should

obvious point is that Georgescu-Roegen disregards the function of fitting theories to the world, which mainly relies on econometrics. The idea of models as investigative instruments in turn is mostly concerned with the predictive character of models and its relevance for policy action. On this point, Georgescu-Roegen's position is more ambiguous, since he clearly asserts that models cannot be an automatic guide for action but may nevertheless contribute to the understanding of economic phenomena and policy making. Finally, his methodological propositions seem to fit best with the idea of modelling as theorising, understood as the formalisation of the concepts and relations of the theory in a mathematical framework in order to examine their logical implications.

Yet, there may be a subtle difference in the sense that modelling as theorising can also be understood as a mean of conceptual exploration, and in particular of concept formation, which supposes that the newly formed concepts were not directly accessible to dialectical reasoning beforehand. This is particularly the case when models are used to categorise different situations related to variations in the assumptions of the model and in their outcomes⁷. Conversely, Georgescu-Roegen insists that “*an arithmomorphic model has no value unless there is a dialectical reasoning to be tested*” (1971, p. 341, italics in the original). This can be interpreted either as a strict precedence of dialectical reasoning compared to the analytical simile and its logical implications, or as a softer claim enabling for concept formation in modelling practices. While it is not possible to remove this ambiguity at the most general level of Georgescu-Roegen's methodological statements, it provides an interesting question to ask when studying the case of the flow-fund model in the following sections.

1.2 The three steps of theory-making: idealisation, isolation and arithmetisation

Summing up, the previous section has shown that despite the gap separating dialectical and arithmomorphic concepts according to Georgescu-Roegen, the latter can perform different theoretical functions to support the former. However, these functions come with a set of principles that should constrain the process of theory-making. The first and the most important one is that there must be a strong connection between the dialectical and arithmomorphic levels. This permeates in particular when Georgescu-Roegen states that an analytical simile “must be for-

be adapted to one's object of study. I believe that the older one provides a more interesting general framework for analysing the practices and methodological claims of Georgescu-Roegen, but I may borrow the labels of the newer one when it appears relevant.

⁷Morgan and Knuuttila present the role of concept formation and categorising in modelling as follows: “The classificatory functions of model using are almost a by-product of the modelling manipulations and experiments that go on in these processes of concept formation. Each run with a model, each slight change in the assumptions, each minor change in the set up, each substitution of a particular element, may give rise to a different result from the previous one with same or almost the same model. It is this variation in outcomes that leads to new classifications. An obvious example in modern economics is game theory, where minor changes in rule, and in matrix numbers, may lead to different outcomes.” (Morgan and Knuuttila, 2012, p. 76)

mulated with the utmost rigor” and that “there is no room in ‘pure theory’ even for pseudo-arithmomorphic concepts, such as price index, cost of living, aggregate production, and the like” (1971, p. 338). More precisely, this condition can be interpreted as requiring that every concept at the arithmomorphic level must correspond to a concept at the dialectical level, and therefore to some entity accessible to the mind. Stated otherwise, there must be a “structural consistency” between both levels.

Isn’t this one-to-one correspondence between dialectical and arithmomorphic concepts weakening the initial distinction? It seems not to be the case, because Georgescu-Roegen adds that an analytical simile displays only one facet of the dialectical concept it aims at representing, and especially, there can be multiple analytical simile corresponding to one dialectical concept. For instance, he considers that the “laplacean” and the “frequentist” conceptions of probability are two analytical similes of the dialectical concept of “random”, or, as he states it, that they “are the two ends of one and the same bridge between human understanding and the actual world” (1971, p. 59). However, the counterpart of this idea is that the “rigour” with which the analytical simile is supposed to represent the dialectical reasoning can never be complete. And Georgescu-Roegen does not provide a clear standard according to which evaluate the relevance of a given arithmomorphic concept in relation to its corresponding dialectical dual.

This issue echoes the issues related to simplifications in the philosophy of economics and modelling. Indeed, a similar form of simplification has been pointed out by the literature on economic models, which underlines that “models typically also constrain the problem at hand” (Morgan and Knuuttila, 2012, p.66-67). It is for instance from this point of view that it considers the debate on the relation between the IS-LM model and Keynes’s *General Theory*. However, this kind of simplification is not defined very accurately by the literature, and Georgescu-Roegen’s approach enables to distinguish two different processes inside it. First, simplifications appear as the consequence of the “arithmetisation” process, to use his own word, between a theoretical argument formulated literally and its representation by a model. As discussed before, this is the main preoccupation of Georgescu-Roegen, and he intended to give it some solid philosophical ground through the distinction between dialectical and arithmomorphic reasoning, that can only partially translate one into the other because of their different conceptual nature. This issue is not very much discussed in the literature, and therefore his contribution on this aspect is quite original.

The second way we can interpret the idea of simplification between theory and model is by an “isolation” of a limited number of entities and relations to be represented in the model which leaves out other concerns⁸. In Georgescu-Roegen’s

⁸Another example of such a process, in addition to the case of the IS-LM model, is the relation between Harrod’s growth theory and Solow’s model. Indeed, Halmayer and Hoover suggest that Solow’s model left out many of the keynesian preoccupations of Harrod’s original approach: “Reformulation of Harrod’s ‘dynamic theory’ in terms of a model - that is, translation between the practices of different interpretive communities - involved serious losses. Because they were not easily modelled through a closed system of differential or difference equations, Harrod’s concerns with the stability of a dynamic path were not understood by the growth modellers.” (Halmayer

approach, this feature also appears and is distinguished from the previous one, even if it is less developed. For instance, he criticises complex macroeconomic models composed of many equations and variables for moving beyond “our mental control”, which according to him is the only possible control in social science due to the lack of measuring instruments. This leads him to support “simple-minded” models as being more informative, which requires to “pick up a few but significant elements from the multitude of cluttering facts” (1971, p. 340). Such an approach is in fact quite similar to that which dominated economic philosophy in the 19th century, in particular according to John Stuart Mill’s conception of economics as an “inexact and separate science” (Mäki, 2012b; Morgan and Knuuttila, 2012). Moreover, in Georgescu-Roegen’s perspective, the idea of “mental control” seems tightly linked with the function of facilitating understanding he assigns to models.

There is an ambiguity however in Georgescu-Roegen’s work, but also in the literature, on the exact stage at which the isolation process happens. But if this idea is to be consistent with his other methodological principles, it seems that isolation of a limited set of relevant factors must already be part of the dialectical reasoning. Indeed, as underlined before, the analytical simile is conceived by Georgescu-Roegen as a tool to check errors and must have a strong structural connection with the dialectical level. Hence, there must be as many acting forces at both levels, even though the arithmomorphic ones will imperfectly represent the dialectical ones. This interpretation leads to understand isolation as an essentially *quantitative* restriction, whereas arithmetisation has consequences at the *qualitative* level.

Finally, this also invites to distinguish isolation and arithmetisation from a third process of simplification which happens with the formation of concepts at the dialectical level. In fact, in Georgescu-Roegen’s work we do not find a detailed account of how one should proceed for this step. We have mentioned before the “esprit de finesse” he borrows to Pascal, but this seems more concerned with valid reasoning than valid concept formation, and, in addition, it is not much developed beyond Pascal’s quotation. However, we find a more interesting hint on this topic in his discussion of Wesley Mitchell’s criticism of neoclassical theory as “imaginary individuals coming to imaginary markets with ready-made scales of bid and offer prices” (Mitchell 1925, quoted in Georgescu-Roegen 1971, p. 319). Indeed, he considers that this criticism misses the right point, and he advocates conversely that “abstraction is the most valuable ladder of any science”, a perspective which he assumes to be that of Schumpeter and Marx as well. Another element in this direction is the claim that the first task of economics should be to construct “an ideal-type that would make ‘pragmatically clear and understandable’ ” the features of economic reality, with an explicit reference to Max Weber. Similarly, in the literature, Weber is identified as one of the important methodological sources of inspiration concerning “idealisation”, and it is underlined that himself considered rational individual economic behaviours and the market as viable ideal-types (Morgan and Knuuttila, 2012, p. 61-62)⁹.

and Hoover, 2016, p. 587)

⁹In fact, Morgan and Knuuttila suggest that ideal-types may not only be considered as mere simplifications of an existing economic reality, but rather as constructions by exaggeration: “[We may interpret] the caricaturing process as something more than the exaggeration of a particular

Therefore, the three different kinds of simplifications operating in economic theory according to Georgescu-Roegen can be schematically summarised as follows: “idealisation” of the real world in the form of dialectical concepts, according to Weber’s ideal-types; “isolation” of a limited spectrum of relevant elements to form a dialectical reasoning; “arithmetisation” to provide an analytical simile and test the logical consistency¹⁰. Moreover, this ordering of the different steps appears as the general trend that economic theorising should follow according to Georgescu-Roegen. Its logic is that we loose in completeness what we gain in understanding and logical consistency as we go along it.

This scheme of Georgescu-Roegen’s methodological position is also useful to analyse the issues it may encounter on its way. As he didn’t focus on these steps of the process, he does not seem to provide a criteria to decide what is a good idealisation or a relevant isolation. More importantly, we have highlighted above that the stage of arithmetisation could not be founded on an objective criteria either since an arithmomorphic concept can only represent an incomplete picture of a dialectical concept. No doubt, this would not bother Georgescu-Roegen who insisted on many occasions that in the last resort only “delicacy and sensitiveness of touch”, as Marshall called it, was relevant (1971, p. 331 and p. 333). However, this is not a very clear guiding principle.

Georgescu-Roegen’s discussion of the distinction between dialectical and arithmomorphic concepts, and of its consequences for the use of models is clearly his most developed and original contribution to the philosophy of economics. However, beyond that, the general outline of his methodology could correspond in many respects to the principles that guided late classical and early neoclassical economists (Hausman, 2007; Mäki, 2012b). This may question Georgescu-Roegen’s traditional presentation as an heterodox economist and a critic of mainstream economics, at least in the second part of his a career.

One of the ways to remove this paradox is to remark that the methodology of mainstream economics in the second half the 20th century was not at all that of the 19th century. In particular, it was transformed by the rise of models as a central tool (Morgan and Knuuttila, 2012), and a switch toward a rather popperian or even instrumentalist point of view (Hausman, 2007; Mäki, 2012b). But Georgescu-Roegen’s methodology is also different from the earlier tradition of mainstream economics in the sense that he agrees with the criticisms addressed to it by historicist and institutionalist schools¹¹. As a consequence, he considers that the relevance of a

feature, rather it involves the addition of features, pointing us to the constructed nature of the exaggeration rather than to it as an idealization, abstraction or isolation of causal factors.” (Morgan and Knuuttila, 2012, p. 62-63)

¹⁰The definitions of these labels given here may not be consistent with definitions found in other places. Morgan and Knuuttila (2012, p. 51) warn for instance that “the term ‘idealization’ is generically used, but it is very difficult to find a single or shared definition”. However, the definitions adopted here appear appropriate to deal with Georgescu-Roegen’s methodology.

¹¹For instance, Georgescu-Roegen explicitly supports the criticism of the historical school regarding the conception of man’s behaviour in classical economics: “Indeed, if man’s economic actions were independent of his cultural propensities, there would be no way to account for the immense variability of the economic pattern with time and locality. [...] The much better faring of standard economics notwithstanding, it is the position of the historical school that is fundamentally the

theory is limited geographically and temporally. Accordingly, the role of theorising should be: first, to produce “a workable body of descriptive propositions for a *given* reality”; and second, to construct an analytical simile from these propositions for “*each* economic reality” (1971, p. 331, my italics). This position is also linked to his belief that qualitative features are highly important in economics. Indeed, it underlines that economic realities in different places are qualitatively different and therefore should be accounted for by different theoretical frameworks, involving idealisation and isolation of the relevant features¹².

More importantly, this perspective shapes his opinion regarding the understanding of a given economic reality through time. Indeed, he insists that qualitative change should be a fundamental aspect of this understanding, but cannot be represented by arithmomorphic concepts. This leads him to distinguish between “dynamics” and “evolution”. The former corresponds to the quantitative change that may occur in an economy which keeps the same qualitative features, and therefore may be represented by an analytical simile such as the conventional differential systems of growth theories. But this kind of representation is only relevant on a limited time-scale, because of “the evolutionary nature of the economic process that precludes a grasping of all its relevant aspects by an arithmomorphic scheme” (1971, p. 330)¹³.

Hence, these considerations on geographical and temporal qualitative variations impose more restrictions on the relevance of theories in Georgescu-Roegen’s methodology, as schematised before by the triptych: idealisation, isolation, arithmetisation. However, Georgescu-Roegen insists that it is no reason to get rid of theory-making in this sense, which in his opinion is still the best way to understanding¹⁴. In particular, his appraisal of the benefits and limits of mathematical models was a much balanced one:

Whenever arithmetization can be worked out, its merits are above all words of praise. My point is that wholesale arithmetization is impossible, that there is valid knowledge even without arithmetization, and that

correct one” (1971, p. 342). On other instances, he praised Veblen for his attention to the role of cultural features in the evolution of the economy (1971, p. 362).

¹²Georgescu-Roegen was particularly interested into the specificities of peasant communities and agrarian economics (1960; 1969a). According to him, the lack of interest for the specific features of these economic realities has important consequences in development theories and policies. For instance, this leads him to deny that fast industrialisation is the best way to development: “In fact, the greater the industrial development achieved by an underdeveloped nation plagued by a predominant, over-populated, and disorganized agricultural sector, the stronger the evidence such a nation offers of the fallacy of the industrialization axiom. There the peasantry is still as poverty-stricken as ever.” (1971, p. 329-330)

¹³Because of this insistence on the evolutionary nature of the economic process, both at the cultural and technical levels, Georgescu-Roegen has had some influence, along with many other authors, on the contemporary school of evolutionary economics, and in particular on Ulrich Witt and the Evolutionary Economics Group (Vromen, 2012, p. 744, n. 8).

¹⁴In this respect, Georgescu-Roegen strongly disagrees with institutionalists, which he presents as opposed to his conception of theory-making: “I wish to observe, however, that the American Institutionalists, though hailing Veblen as their prophet, have inherited little from him besides an aggressive scorn for ‘theory.’” (1971, p. 321, n. 14)

mock arithmetization is dangerous if peddled as genuine. (Georgescu-Roegen, 1971, p. 15)

With these considerations in mind, let us now turn to the construction of his flow-fund model of production, which constitutes his most developed analytical contribution after the 1970s.

2 The flow-fund model of production

Georgescu-Roegen's interest for the economics of production dates back to his early career, when he investigated for the first time the impact of limitational factors of production on the theory of marginal productivity pricing (1935). He got interested in this topic again when he came back to the US, after his return to Romania in the 1940s, and participated actively to the Cowles Commission conference on linear programming in 1949 (Koopmans, 1951). In the 1950s, he became more and more dissatisfied with the neoclassical production function and marginal productivity pricing, which he saw as particularly inadequate in overpopulated countries, a situation he had experienced in Romania (1955).

But his criticism of the production function and the formulation of his alternative framework were really developed for the first time in a conference of the International Economic Association in 1965 (1969b). A few years later, it was the subject of his Ely lecture at the 1969 meeting of the American Economic Association (1970)¹⁵. However, the most complete exposition of his initial attempt to reconstruct the economics of production is to be found in chapter IX of *The Entropy Law and The Economic Process*, published shortly after (1971). There, he fully exposed the conceptual foundations of his analysis of production and used it to identify flaws in traditional representations of production.

Before proceeding forward with the examination of this framework, I should recall the duality of my aims in this section. On the one hand, I want to use the interpretation of Georgescu-Roegen's methodology presented in section 1 in order to make sense of the process by which he builds his theory of production. In this sense, it functions as a reading grid that enables to reconstruct the structure of the theory, which is only implicit in Georgescu-Roegen's exposition. But while this may provide some interesting insights, we should also take care of acknowledging the points on which it seems to deviate from his methodological principles. On the other hand, this process of theory-making gives the opportunity to learn about his methodology through the practice. This may reveal cases where obstacles prevent from following the explicit methodology accurately, and therefore its limits as a practical guide. But it may also help question some of the ambiguities identified earlier in this methodology, and even provide some complementary principles that

¹⁵Its publication the next year in the American Economic Review (AER) is very symptomatic of Georgescu-Roegen's heterodox turn and marginalisation: while he used to publish in first rank reviews such as the AER, *Econometrica* or the *Quarterly Journal of Economics*, after this article he never did again and only published in lower rank reviews such as the *Southern Economic Journal* or the *Atlantic Economic Journal*.

were not spelled out explicitly. Hence, the increase in understanding goes both ways: from methodology to practice; and from practice to methodology.

2.1 Conceptual foundations of the flow-fund model

To begin with, one of the reasons of Georgescu-Roegen's dissatisfaction with the existing economics of production is the lack of conceptual rigour in the neoclassical definition of the production function, which he presents as an "illustration of the harm caused by the blind symbolism that generally characterizes a hasty mathematization" (1970, p. 1). Indeed, he recalls that it was initially introduced with the simple remark that "the product being a function of the factors of production we have $P = f(a, b, c, \dots)$ " (Wicksteed 1894, quoted in Georgescu-Roegen 1970, p. 1), and he blames it for its imprecision, in particular in the definition of the notions of input and output. Moreover, he suggests that this lack of conceptual rigour has been going worse as economists got use to this terms even though they never precisely defined it, especially in manuals such as those of Paul Samuelson or Kenneth Boulding. This especially led to a confusion on whether the symbols correspond to quantities or quantities per unit of time, and finally to the idea that both formulations were equivalent. However, Georgescu-Roegen shows that this equivalence would lead to the conclusion that any production process must have constant returns to scale¹⁶. As a result, he concludes that "this imbroglia is the direct consequence of our acceptance of Wicksteed's symbolism without first probing its validity as an analytical mirror of actuality" (1970, p. 2).

Therefore, his own approach tackles this problem and tries to give rigorous conceptual foundations to the economics of production. His first step in this direction is to give a general definition of the notion of "process" in science in order to specify the nature of the production process. This definition relies on the idea that the process is defined by a "boundary" with two components: the "frontier" which separates the process from its "environment" at any point in time; and the "duration" which sets the time boundary of the process. However, as Georgescu-Roegen acknowledges, the definition of this boundary is already confronted to the dialectical nature of reality, which he describes as "a seamless Whole". He illustrates this problem with the difficulty of determining if a particular atom is part of a living organism or of its environment, or, in economics, to establish if "the hired worker in a capitalist system [is] in essence owned by the capitalist" (1971, p. 212). Nevertheless, according to Georgescu-Roegen, analysis must overcome the issue and "proceed by some heroic

¹⁶If $Q = F(X, Y, \dots)$ is the production function expressed with quantities, and $q = f(x, y, \dots)$ the production function in quantities per unit of time, then $Q = qt$, $X = xt$, $Y = yt, \dots$. The first formula then becomes $qt = F(xt, yt, \dots)$, and using the second formula we get $f(x, y, \dots)t = F(xt, yt, \dots)$. Evaluating this last formula at $t = 1$ yields that $f(x, y, \dots) = F(X, Y, \dots)$ and that F is homogeneous of degree one.

Though very simple, when Georgescu-Roegen presented this idea for the first time, Don Patinkin, who was his discussant at the conference of the International Economic Association in 1965, thought there was a mistake and simply refused to discuss the rest of the paper. He later acknowledged he was wrong. See the discussion in Georgescu-Roegen (1969b), and the retrospective comments in Georgescu-Roegen (1992).

simplifications”. And he concludes that:

The first element, therefore, that the analytical picture of a process must necessarily include is the analytical boundary. *No analytical boundary, no analytical process.* (Georgescu-Roegen, 1971, p. 213, italics in the original)

Is this approach consistent with the interpretation of Georgescu-Roegen’s methodology formulated in section 1? This question raises a troubling element in this first exposition of his conception of the production process, namely his insistence on presenting it from the beginning as an “analytical” perspective. Conversely, my interpretation of his methodology of theory-making highlighted that the understanding of economic reality must start at the dialectical level, and is essentially an intuitive one that relies on the mind as an instrument of observation. From this point of view, the concept of boundary would be interpreted first as a dialectical one, intended to capture the intuitive understanding of a production process as being delimited in space and time. And it would only appear as an arithmomorphic concept in a second time, according to the principle of structural consistency between the two levels. However, beyond a few illustrations with some concrete examples of processes, the notion of boundary at the dialectical level is not much elaborated by Georgescu-Roegen, who clearly insists more on the arithmomorphic side of the concepts of process and boundary. While this is linked to his purpose of building an alternative *model* of production, it blurs the fundamental nature of these concepts as “idealisations” of our sensible experience of the real world. Using my interpretation of Georgescu-Roegen’s methodology as a reading grid helps making this point clearer and in this sense provides a more consistent understanding of the elementary structure of his theory of production.

Once the idea of boundary is settled, the analysis of the production process so defined “reduces to recording only what crosses the boundary” (1971, p. 215). Georgescu-Roegen identifies two distinct categories of elements crossing the boundary. First, there are the “flow” elements that either enter or leave the process, but never both. At the analytical level, and on the duration of the process $[0, T]$, a flow is recorded by a function $E(t)$ of its cumulative amount until t , counted negatively for inputs and positively for outputs. The inputs are consumed inside the process, whereas the outputs are created. In a general production process, this category would include: natural resources R and intermediary goods I as inputs; products Q and wastes W as outputs. Second, there are elements that enter and leave the process without major modifications of their identity. Hence, these elements are not transformed by the process but are used to produce services, and this is why Georgescu-Roegen labels such elements as “funds” of services. Mathematically, he suggests to account for them with a function $S(t)$ of the cumulative services they have performed at time t . And in this category, he includes “Ricardian land” L , in reference to the importance of this factor in Ricardo’s analysis, capital equipment K and labour power H . Therefore, Georgescu-Roegen represents analytically the production process as a whole by the following vector of functions defined on the

interval $[0, T]$ ¹⁷:

$$\left[\overbrace{R(t), I(t)}^{\text{input flows}}, \overbrace{Q(t), W(t)}^{\text{output flows}}; \overbrace{L(t), K(t), H(t)}^{\text{funds}} \right] \quad (1)$$

However, the distinction between flows and funds raises some conceptual issues, which Georgescu-Roegen himself acknowledges. One of them concerns the assumption that fund elements come out of the process unaltered. Georgescu-Roegen initially admits that there is necessarily a qualitative change of funds between these two moments: a worker comes in the process rested and leaves it tired; a tool is new when it enters and used when it goes out; and land exploitation drains nutrients from the soil (1971, p. 216). It is all the more important for him because he considers that this universal “wear and tear” is the direct consequence of the entropy law, which he regards as the main driver of qualitative change in the material environment¹⁸. But, in line with his description of qualitative change as a an essentially dialectical phenomena in his philosophy of economics, Georgescu-Roegen suggests that it cannot be accounted for by analysis. The latter must therefore proceed once again to a “heroic simplification” and assume that funds come out of the process unchanged:

However, the impasse can be resolved and the solution comes straight out of the economic literature of older vintage. It is the idea of capital equipment *being kept as a constant fund by the very process in which it participates*. Strictly interpreted, this idea is a fiction. A process by

¹⁷The variables in this formula may cover a great variety of entities. For instance, in resources R , Georgescu-Roegen includes elements as diverse as “the solar energy, the rainfall, the ‘natural’ chemicals in the air and the soil, the coal-in-the-ground, etc” (1971, p. 231-232). However, this should not be interpreted as the adoption of an aggregated view of the production process. Indeed, Georgescu-Roegen reiterates in many occasions his criticism of the use of aggregated variables. See also section 2.3 below for a more detailed discussion of this aspect.

¹⁸Georgescu-Roegen is well known for his insistence on the influence of thermodynamic laws on the economic process. Briefly, thermodynamics can be defined as the science of the transformations of energy, and is essentially constituted of two principles. The first principle states that energy can change its form, from movement to heat by friction for instance, but that its quantity is conserved. The second principle in turn specifies what are the possible transformations between the different forms of energy. In particular, the work of Sadi Carnot at the beginning of the 19th century shown that the thermal energy of a heat engine cannot be fully transformed into mechanical energy, whereas the opposite is possible. This also means that the possible transformations of energy are always in the sense of a “qualitative degradation”. And this statement can be reformulated using the concept of “entropy”, which can be defined in a non technical way as an index of the relative amount of dissipated energy in a system. According to this, the second principle may also be understood as the increase of the entropy of an isolated system towards a maximum, also called the “entropy law”.

This is the root of Georgescu-Roegen’s understanding of the role of natural resources, and he asserts that “from the purely physical viewpoint, the economic process is entropic: it neither creates nor consumes matter or energy, but only transforms low into high entropy” (1971, p. 281). However, it is not of prime importance for my purpose here and I will therefore not deal further with this question. See for example Poirier (2014) for a conceptual introduction to thermodynamics, and Cleveland and Ruth (1997) for a survey of its status in Georgescu-Roegen’s thought.

which something would remain indefinitely outside the influence of the Entropy Law is factually absurd. But the merits of the fiction are beyond question. [...] All it means is that the *specific* efficiency of every piece of capital is kept constant. (Georgescu-Roegen, 1971, p. 229, italics in the original)

Yet, as a counterpart to this assumption, Georgescu-Roegen proposes to take into account the activities dedicated to the maintenance of funds. Capital equipment for instance must be repaired and kept in good working conditions, but the problem is that the maintenance tools themselves would need to be maintained¹⁹. According to him, this issue is still another manifestation of the dialectical nature of reality which analysis cannot fully handle and hence must circumvent by simplification. In this case, he suggests to include in the representation of the process a maintenance flow M coming from outside to keep capital efficiency constant, and to ignore the wear and tear of the worker, whose restoration is achieved by domestic activities outside the process.

Hence, Georgescu-Roegen does not hide the issues underlying the concept of fund, and instead makes very clear the simplifications to which he proceeds because they appear the most relevant to him. His assumptions have nevertheless been criticised by Kurz and Salvadori in their comparison of the flow-fund model with the approaches of Sraffa and Von Neumann. Indeed, the latter have suggested to take into account the ageing of capital equipment as an indicator of its decreasing efficiency and to consider used capital at each time period as a joint-product of the process. While Georgescu-Roegen thought this would lead to unnecessary analytical complications, Kurz and Salvadori underline that it enables to study the “economic lifetime” of machines, that is the age at which they become economically obsolete even though they are still technically functioning (Kurz and Salvadori, 2003, p. 497).

But we can make sense of this criticism in the framework of Georgescu-Roegen’s methodology. Indeed, my interpretation of the latter enables to understand the assumption of unaltered funds as part of the step of “isolation” of the relevant features of economic reality to be accounted for. While the qualitative change of funds is an undeniable aspect of this reality, as acknowledged by Georgescu-Roegen himself, accounting for it would greatly complicate his theory of production. Even more importantly, this situation highlights that the step of isolation is intimately connected to the issue of which problems the model is designed to deal with. Here, the question is whether economical obsolescence is an important feature of economic change or not. More precisely, is it more important that the economic change brought about by technological progress which implies both technical and economical obsolescence of older capital equipment? Even though Georgescu-Roegen did not explicitly consider this question, his insistence on the qualitative change brought about by evolution in the economic process, as underlined in section 1.2, is clearly more concerned

¹⁹As an illustration, in agriculture, Georgescu-Roegen states that a spade requires a file to be maintained, which in turn requires a wire brush to be maintained, etc., drawing us “into a regress which might not end until we have included in the process in question a very large part of the entire production sector of the economy” (1971, p. 229-230). The case is even more intricate for the labour fund whose “maintenance” is achieved in the “household process”.

with this latter problem than with the mere economical obsolescence²⁰. This tends to show that the appropriate isolation is the result of some *a priori* ideas on the most important features of the production process that the analytical model should account for. As a consequence, these simplifications may always be subject to criticism from those who believe in other preconceptions on the purpose of a theory of production.

Proceeding forward, let us now consider Kurz's and Salvadori's claim that, because of their criticism of the flow-fund model, the "flow-flow" models in the spirit of Sraffa and Von Neumann are superior. In fact, this is somewhat misleading since their argument does not totally abolish the distinction between flows and funds. First, in Georgescu-Roegen's analysis of production flows are consumed or created by the process while funds come in and out unaltered. Even if the latter assumption is weakened to account for ageing capital equipment, the possibility of reusing it in successive periods of production is still one of its most important characteristics. Second, and more importantly, Kurz and Salvadori explicitly hold to "Georgescu-Roegen's important distinction between the 'agents of a process' of production (funds) and its flow elements 'which are used or acted upon by the agents'" (Kurz and Salvadori, 2003, p. 496).

This second aspect of the distinction is made clearer and more fundamental by Georgescu-Roegen when he examines the difference between stocks and funds. On the one hand, stocks enter the production process as flows, even though flows not necessarily come from stocks: for instance, fossil fuels come from a pre-existing stock but not solar energy. Funds on the other hand produce services. According to Georgescu-Roegen, the important difference is that the rate at which a stock may provide a flow is not limited, whereas "the use of a fund [...] requires a duration", which is "determined within very narrow limits by the physical structure of the fund" (1971, p. 226)²¹.

However, Georgescu-Roegen's statement hides a more intricate situation. Indeed, as the flow-fund model itself shows, in general, processes require both a stock and a fund. Consider for example the extraction of oil: it requires a deposit of oil in the ground and a pump-jack that pulls it out through a well. But Georgescu-Roegen's distinction remains relevant: the flow of oil coming out of the stock may be as big as one wishes provided we have enough wells and pump-jacks; whereas with a given number of wells and pump-jacks we may only get oil out of the ground at a certain rate, whatever the size of the deposit. This underlines an asymmetry between both

²⁰An indirect reference to this is his remark that "in places that the jet planes cannot yet reach we see hundreds of DC-3 planes, some twenty years old, doing now as good a job as when they were new" (1971, p. 229). What this example attempts to show is that the ageing of capital is not a crucial factor as long as the economic service considered cannot be performed by an improved technology.

²¹Georgescu-Roegen illustrates this point with the following example: "If the count shows that a box contains twenty candies, we can make twenty youngsters happy now or tomorrow, or some today and others tomorrow, and so on. But if an engineer tells us that one hotel room will probably last one thousand days more, we cannot make one thousand roomless tourists happy now. We can only make one happy today, a second tomorrow, and so on, until the room collapses." (1971, p. 226)

factors of production: the fund element is limiting regarding the rate of production; while the stock is limiting regarding the total output of the process²².

In the end, what precedes shows that at the dialectical level, that of our intuitive understanding of “commonsensibles”, the distinction between flows and funds in Georgescu-Roegen’s analysis of production rests on two different characteristics. One of them is related to the durability of the elements: flows come in but not out, or the other way round; while funds come in and out unaltered, or at least are reusable in another production period²³. The other concerns the respective role of the elements inside the process: flows are objects of the transformation; while funds are agents acting upon them. But this raises an important question: are these two ways of characterising flows and funds equivalent?

The conceptual issue raised by this question can be noticed in Georgescu-Roegen’s own writings. For instance, he asserts that “the clover seed in a process the purpose of which is to produce clover seed is a fund”, even though he recognises that the seed undergoes “a qualitative change inside the process” (1969b, p. 511). The problem is that the clover seed is indeed a fund according to the definition of durability above, but not according to the its role inside the process since it is truly an object of the agricultural process. Similarly, Georgescu-Roegen suggests that “a space rocket would at present be classified as a consumable input; yet in the technology of tomorrow it may become a durable input used successively in several space flights” (1971, p.225). In this case, the space rocket is always an agent of the process, but it may be durable or not²⁴.

Therefore, the equivalence between durable elements and agents of production that supports the definition of funds is not always satisfied. The point confirms that what we are dealing with here is the step of idealisation by which one attempts to abstract ideal-types from the reality of production processes, with the mind as unique instrument of observation. And indeed, even though he doesn’t present it as such, Georgescu-Roegen warns that “the classification is, of course, dialectical”. According to this view, such complications are inevitable, but after acknowledging them,

²²Georgescu-Roegen also argues that services of funds and flows of stocks differ from the dimensional point of view: the unit of a flow has the dimension of a substance (pounds,quarts, feet,...) and the rate of a flow the mixed dimension of substance per time; conversely, a service corresponds to the use of a fund for a certain time and hence has a mixed dimension of substance multiplied by time, while the rate of service depends on the size of the fund and has the dimension of a substance.

²³This definition of durability is not concerned with what actually happens in the process, but only with the relation between what comes in and out, as Georgescu-Roegen explains: “Inputs can be classified into nondurable and durable in a manner that meets the requisites of analysis if we adopt a relative criterion. In relation to a given process an input is only used (but not consumed) if it can be connected with an output element by reason of identity of substance like the clover seed in growing clover seed — or sameness of object — like the painter’s ladder. If this is not the case, the input is consumed in the process.” (1971, p.225)

²⁴This issue is also reflected by some interpretations of Georgescu-Roegen’s flow-fund model by other authors. Beard and Lozada, for instance, suggest that the distinction between flows and funds will depend on the duration of the process considered: funds may become flows if the time-scale is too large to consider that they come out unaltered or that they are reusable in another production period (Beard and Lozada, 1999, p. 68). Yet, if we consider funds as agents of the production process, then this characteristic is independent of the duration.

we should proceed and consider this framework as a sufficiently good approximation of the real world for the purpose of economic analysis.

Hence, from what has been said in this section, the different steps of Georgescu-Roegen’s explicit methodology of theory-making can be identified in the foundations of the flow-fund theory of production. The notions of “process”, “boundary”, “flows” and “funds”, have appeared as primary concepts built by “idealisation”, and on which the whole theoretical edifice rests. The concept of fund has been the subject of particular attention because it is at the center of the step of “isolation” which determines in particular the kind of problems the model is designed to address. Moreover, the efforts Georgescu-Roegen dedicates to the construction of this conceptual structure show the real nature of his criticism of the neoclassical production function: it is deprived of such solid conceptual foundation elaborated prior to the model, and therefore amounts to “modelling without theory”²⁵. Stated differently, it grasps the first mathematical tool at his disposal, a “point function”, without any attention for its consistency with our intuitive understanding of the production process. Conversely, Georgescu-Roegen shows that, at the most general level, this intuitive understanding is only consistent with the representation of the process by ²⁶:

$$\overbrace{[R(t), I(t), M(t)]}^{\text{input flows}} \quad \overbrace{[Q(t), W(t)]}^{\text{output flows}} \quad \overbrace{[L(t), K(t), H(t)]}^{\text{funds}} \quad (2)$$

While this helps better understand the conceptual part of his criticism, in the next sections we explore its practical consequences, in the sense of the logical implications we can derive from these foundations.

2.2 The organisation of processes and the production function

The representation of the production process in 2 brings forward another important aspect of Georgescu-Roegen’s analysis of production, namely that it is *time-explicit*. In order to understand further what we might learn from this representation, Georgescu-Roegen suggests to consider first the process by which one unit of the output is produced, for instance one table. He calls such a process “elementary” because “every production system of any type whatsoever is a system of elementary processes” (1971, p. 235). In such a process, funds will most probably be idle a good deal of the time as one step of the process is operated after another. And Georgescu-Roegen points out that this “is not the result of our own fault or wish” but the “unavoidable consequence of the material conditions of the process itself”²⁷.

²⁵The expression is mine but intends to capture the meaning of Georgescu-Roegen’s criticism based on his own practice of theory-making. “Theory” in particular should be understood as dialectical concepts and reasoning, not in the sense of “theoretical science” used by Georgescu-Roegen.

²⁶This equation is similar to 1, except that, for the sake of completeness, we have introduced the maintenance flow M defined above.

²⁷Georgescu-Roegen illustrates these material constraints with the following example: “A superficial observation of a cabinet maker at work should suffice to convince us of the general validity of

According to him, one of the most important aspects of economic activities consists in reducing the idleness of the funds by an appropriate combination of elementary processes. In this perspective, he distinguishes three kinds of organisation of production. The first one is the production in “series”, where elementary processes are performed one after the other, so that one unit of output is produced every T , with T the duration of the elementary process. Georgescu-Roegen associates this organisation with the work of the craftsman whose demand is too low to be interested in performing more than one process at a time. However, if the demand rises at n products per period of production T , n elementary processes might be arranged in “parallel”, which means that they start and end at the same time. If formula 2 represents the elementary process, then these n processes in parallel are represented by:

$$[nR(t), nI(t), nM(t), nQ(t), nW(t); nL(t), nK(t), nH(t)] \quad (3)$$

Obviously, this organisation of production does not reduce the amount of funds necessary since their periods of activity and idleness happen at the same time in all elementary processes. There is however one case in which it might be interesting: when a fund has the capacity to perform more than one elementary process at a time, as illustrated by a large bread oven. If the elementary process involves various funds, then, to use each fund at full capacity on its period of activity, the number of parallel elementary process must be a multiple of m , the least common multiple of all funds capacities.

The other possibility to reduce the idleness of funds is to work out an organisation such that when a fund is idle in one elementary process it can be used in another one. In order to do so, Georgescu-Roegen shows that the duration of the process must be split in a certain number of regular intervals, so that each period of fund activity or idleness corresponds to an integer number of such intervals. Mathematically, the length d of the regular intervals is the greatest common divisor of all the durations of these periods²⁸. In order to maximise fund utilisation as in the parallel organisation above, every d , m elementary processes must be started. Then there will be $k = T/d$ such starting points for processes, and a total of km processes started during the duration T ²⁹. Therefore, this production “in line” utilises the full capacity of every fund at every instant of time, and in this sense, it represents the most efficient organisation of production. According to Georgescu-Roegen this is typically the

this truth. The saw, the plane, the sander, etc., are never used simultaneously in the production of a table considered by itself. Every tool is used by turns; in the meantime it lies idle.” (1971, p. 236)

²⁸To be mathematically rigorous, this presupposes that all the durations are related to each other by rational numbers. If this is not the case, because of the density of rational numbers, we can always achieve this by lengthening the durations with as small a variation as we want. Hence, this conditions does not restrict the validity of this proposition.

²⁹Georgescu-Roegen apparently makes a mistake when he states that “the intervals between two consecutive batches is T/d , where d is the greatest common divisor of T and of the intervals during which the various kinds of funds are needed in an elementary process” (1971, p. 238, n. 43). As explained above, d is rather the interval between two starting points for processes and T/d the number of such starting points.

organisation associated with the “factory system”, and this leads him to claim that this system is “one of the greatest economic inventions in the history of mankind” (1971, p. 248).

But he also highlights that this organisation is only possible if “the demand for a product is sufficiently large” (1971, p. 238). In fact, the condition appears even more stringent than this: the average demand on the duration T of the process must be a multiple of km . If this is the case, the full utilisation is achieved by performing in parallel the necessary number of in line processes as above. And even though Georgescu-Roegen himself didn’t notice that, this result appears as a formal explanation of the “multiple principle” suggested by Charles Babbage in the early nineteenth century, which implies that the most efficient organisation can be maintained if and only if the demand increases by discrete jumps (Marzetti, 2013, p. 212).

Instead Georgescu-Roegen related the role of demand in the previous results to Adam Smith’s tenet that “the division of labor is limited by the extent of the market” (quoted in Georgescu-Roegen 1971, p. 249, n. 57). Indeed, in the flow-fund framework, the division of labour implies a specialisation of tasks that implies a qualitative distinction between labour funds. But the multiplication of qualitatively different funds would most probably result in the reduction of the length of the regular intervals d , hence in the increase of k and km ³⁰. Hence, “if the demand flow does not increase in the same proportion, specialization would only result in costly idleness” (1971, p. 249).

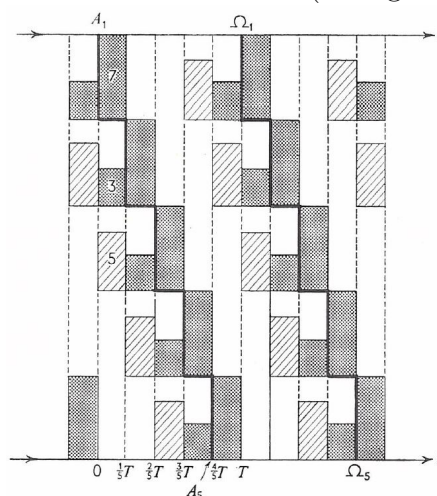
This discussion of the different organisational patterns of production processes illustrates very well the relation that Georgescu-Roegen’s methodology suggests between dialectical and arithmomorphic reasoning. First, it is intimately linked with the understanding, at the conceptual level, of funds as “agents” of the production process, which use requires time. It is this property in particular that enables to define the regular interval d from the set of activity and idleness durations of the different funds. Second, at each and every step the argument is developed simultaneously: at the dialectical level, relying on the abstract concepts of funds and flows as well as on more concrete illustrations in order to improve the understanding of production processes; and at the analytical level, which enables to make more accurate the definitions, the conditions and the properties of these different patterns.

As a consequence, it is also a very good illustration of the two functions that Georgescu-Roegen attributes to analytical similes: checking for errors in existing theories; and facilitating understanding. On the one hand, the combinatorial results obtained by Georgescu-Roegen vindicate Babbage’s and Smith’s theories, and provide them with a rigorous analytical basis³¹. On the other hand, the different

³⁰In the example of the cabinet maker above, this could be illustrated by one worker performing two different cuts with the saw that would be split into two workers each performing one of the cuts. If d_0 was the original length of the regular intervals, and d_1 the one after separating tasks, then d_1 must be a divisor of the intervals associated with both tasks and not only of their sum as before. It is therefore smaller or equal. And it will be strictly smaller if d_0 did not divide one of the two new intervals, a situation which will necessarily happen as tasks are separated in more and more specialised ones.

³¹More generally, these results show the potential of Georgescu-Roegen’s flow-fund model as a

Figure 1: The factory process with two funds (Georgescu-Roegen, 1969b, p. 517)



patterns of organisation can now be exposed and manipulated in analytical schemes. The graphical illustrations in particular, such as that in figure 1³², facilitate the understanding of how the factory system eliminates fund idleness.

Finally, the organisation of production processes at the micro level shows that the flow-fund theory performs the kind of concept formation by categorisation identified by Morgan and Knuuttila (2012). From this point of view, the categorisation between processes in series, in parallel and in line is achieved in part at the dialectical level as an “idealisation” of our understanding of different concrete situations, from the workshop of a craftsman to the factory. But these categories are also secondary concepts derived as relations between the primary concepts of process, flows and funds. In this sense, their understanding is also drawn from the analytical model which enables to identify more accurately their properties by logical implications derived from the primary concepts, especially in the more elaborated case of in line processes. Hence, we can say that there is a retroactive effect of the analytical simile on the structure of the theory by its contribution to the formation of new concepts. This supports the idea that the process of theory-making is not as linear as our schematic representation of Georgescu-Roegen’s methodology in section 1.2 initially suggested.

As we have seen at the beginning of the previous section, one of Georgescu-Roegen’s initial motivations to build a rigorous analysis of production was his dis-

tool for studying the organisation of production processes at the micro level. This line of research has been further developed by a certain number of works in the field of industrial economics. See Marzetti (2013) for a survey.

³²The process represented by this figure relies on two funds that correspond to the two different shaded areas. Horizontally, it represents the successive stages of an elementary process and the amount of funds of different kinds it mobilises. The bold black line separates successive elementary processes. Within the duration T , five processes are started in line. Vertically, the figure represents all the funds mobilised by the different elementary processes at one time. At every time, ten funds of the first kind and five of the second are active. They periodically shift from one process to another, so that they are never idle, according to the definition of the factory process.

satisfaction with of the neoclassical production function. Hence, after setting the conceptual foundations of his own approach, he compares both frameworks. Since the production function is supposed to represent a set of different recipes, the prerequisite is to know how to represent it in the flow-fund model. One recipe being given by formula 2, it is possible to represent such a set by an equation relating the output Q to the other elements of the production process:

$$Q(t) = \mathcal{F}[R(t), I(t), M(t), Q(t), W(t); L(t), K(t), H(t)] \quad (4)$$

From this point of view, Georgescu-Roegen suggests that we better understand one of the mistakes of neoclassical theory of production: a production process at the most general level is not described by “a relation from *a set of numbers to one number*” but by “a relation from *a set of functions to one function*”, also known as a “functional” (1971, p. 236, italics in the original). The main difference is that the second representation explicitly involves time. Therefore, the same total quantities of flows and funds may be used with different time profiles which would result in different profiles production. Moreover, Georgescu-Roegen warns that this equation is not defined for any vector of functions on the right. It must represent a well-defined production process, what he calls a “feasible recipe”, not just an abstract vector³³.

Even though the production function appears far from the general representation of a set of feasible recipes in the flow-fund model, Georgescu-Roegen shows that it might be related with the representation of the factory system. More precisely, he considers a factory functioning at its stationary level, which means that from the beginning we have a set of elementary processes at different stages and the product starts to flow out, as represented in figure 1. Moreover, he assumes that the process is continuous in a strong sense: an elementary process is started at every moment, which implies that all flows and funds services are linear functions of time³⁴. Both assumptions lead him to introduce the concept of “process-fund” \mathcal{C} to denote the set of all elementary processes at different stages. With these specifications, denoting the rates of flow by q, r, i, w and the sizes of funds by L, K, H, \mathcal{C} , formula 4 becomes:

$$(qt) = \mathcal{F}[(rt), (it), (mt), (wt); (Lt), (Kt), (Ht), (\mathcal{C}t)] \quad (5)$$

Since each function is fully defined by its rate, this formula is equivalent to a relation between rates of flows and services:

$$q = F(r, i, m, w; L, K, H, \mathcal{C}) \quad (6)$$

³³However, Georgescu-Roegen does not examine the relevance of another implicit assumption: equation 4 assumes that if we are given the function for the flows and funds on the right, then there is only one possible function for the product flow on the left. This postulate seems rather natural and raises no obvious counter-example, but at the same time it has not been examined in detail by Georgescu-Roegen, and hence might still hide some complications.

³⁴This assumption best fits with the representation of industries producing continuous materials such as glass, cement, etc.

But it is also equivalent to a relation between the quantities of flows and services until any time t , where t must explicitly appear in the relation:

$$qt = \phi(rt, it, mt, wt; Lt, Kt, Ht, Ct; t) \quad (7)$$

However, according to Georgescu-Roegen these equations can be refined to account for the specific properties of the different factors of production (1971, p. 242-243). First, as we have seen above, in his framework, funds determine the maximum rate of functioning of the process. Since in the factory system, the utilisation of funds is optimal, it means that they determine the actual rate of functioning, and in particular the rate of output. Hence, there must exist a relation³⁵:

$$q = f(L, K, H) \quad (8)$$

Once the fund capacities are set, the relations between flows result from the laws of conservation of matter and energy³⁶. More precisely, Georgescu-Roegen distinguishes the wastes linked to the wear-and-tear of capital equipment w_1 from that linked to losses in the transformation process w_2 , and he suggests that:

$$\begin{aligned} w_1 = m = m(K, H) \\ q = g(r, i, w_2), \quad w_2 = w_2(L, K, H) \end{aligned} \quad (9)$$

In addition, Georgescu-Roegen asserts that “ g must be homogeneous of the first degree”, which he relates to “a familiar argument: double the amounts of timber, of impregnating material, *and of waste*, and the amount of railroad ties will necessarily double, too” (1971, p. 243, italics in the original).

Together, these equations are supposed to describe more accurately the general features of the factory system. But how do they relate to the conventional production function of neoclassical economics? As we saw at the beginning of section 2.1, one of the issues raised by Georgescu-Roegen regarding the production function was the meaning of its variables: are they quantities or quantities per unit of time? From his analysis, Georgescu-Roegen suggests that the second possibility corresponds to 6 and is formally correct. However, he underlines that it “does not tell us what the corresponding system *does*, but only what it *may do*” (1971, p. 241, italics in the original). In particular, he insists that the time variable is absent of this representation and that in order to represent the effective production it has to be

³⁵In fact, Georgescu-Roegen argues that capital and land by themselves determine a maximum rate of output and the amount of labour force necessary to achieve it. But he adds that “the human element being as variable as it is in actuality, [the maximum rate of output] is rather an unattainable limit”, and that “the actual rate of product flow depends on the quality as well as the size of the personnel employed”, which leads him to equation 8 (1971, p. 242).

³⁶This step shows that the foundations of the flow-fund model are not only based on an “intuitive” understanding of the production process, but also on “interdisciplinary consistency” with the disciplines considered as relevant for the subject, in this case thermodynamics. We don’t deal with this other implicit aspect of Georgescu-Roegen’s methodology here, and leave it for further examination. See Couix (2018) for a discussion of this methodological principle in Georgescu-Roegen’s criticism of natural resources economics.

introduced back again under the form of the “working day of the factory” δ (1971, p. 245), such that the daily output Q is given by:

$$Q = \delta q = \delta F(r, i, m, w; L, K, H, \mathcal{C}) \quad (10)$$

According to Georgescu-Roegen, this apparently minor modification is in fact very important. At the theoretical level, he thinks that the omission of the length of the working day is a “regrettable, albeit understandable, regress from Marx’s analysis of the production process in which the time factor [...] occupies a quite prominent place” (1971, p. 245). At the practical level in turn, he believes it has hidden that “one of the ‘secrets’ by which the advanced economies have achieved their spectacular economic development is a long working day”. This leads him to insist on the role of the working day as a lever in economic development policies, especially in under-developed countries “where the legal regimen of the eight-hour day [...] is a patent incongruity, if not a planned anachronism as well” (1971, p. 247).

Moreover, for Georgescu-Roegen, this omission of the time factor is not circumvented by the interpretation of the conventional production function as a relation between quantities. Indeed, he suggests that “the relation between the quantity of product and the quantities of flows and services must include time as an explicit variable — as in [7]”. This point is linked to the fact that Georgescu-Roegen does not suppose that production processes have constant returns to scale. However, what he had apparently not seen is that constant returns to scale relative to the flows are implied by the relations of conservation 9, since he has explicitly assumed that g is homogeneous of the first degree. From this, it is straightforward to show that F also has constant returns to scales in relation to the rates of flows. Hence, only in the case of funds alone, as in equation 8, constant returns to scale may not prevail. Otherwise, the interpretation of the production function as a relation between quantities appears valid, even without time as an explicit variable.

Even though Georgescu-Roegen’s claim happens to be wrong, it is interesting to consider the function of the flow-fund model underlying this reflection. Indeed, his purpose here is to identify a conceptual error in the conventional interpretation of the production function. This is done by considering a more general theory of production with solid conceptual foundations, formalising an analytical simile of this theory, and examining the restricted conditions under which it may formally coincide with the neoclassical production function. These conditions of consistency in turn tell us what are the relevant interpretations of the production function, that is they allow us to check the conceptual consistency of the theory. This shows that the function of “checking” that Georgescu-Roegen attributes to analytical similes is broader than the mere logical consistency. In fact, since his claim is wrong, we can deduce that both interpretations of the production function, as a relation between quantities and as a relation between quantities per unit of time, are conceptually valid according to his own theory, at least as far as flows are concerned.

However, this does not mean that both frameworks are completely equivalent at the conceptual level. Instead, Georgescu-Roegen’s analysis retrains the spectrum of relevance of the production function, because equations 6 or 7 can *only* describe

a factory system with in line organisation, which is not possible to implement for any production process. Indeed, one of the requirements for this organisation is that an elementary process can be started at any moment, a condition which is especially not met by sectors that depend on seasonal factors or natural cycles. The analytical consequence is that activities such as agriculture can be fully described only by a functional such as 2, but not by a simple production function. This has some important economic consequences, especially because a process that cannot be arranged in line necessarily a certain degree of fund idleness. In Georgescu-Roegen's opinion, this is the root of both seasonal unemployment and over-capitalisation in agriculture, and it must be accounted for in economic policies, in particular in underdeveloped agricultural countries (1971, p. 252). As suggested before, this contributes to checking the conceptual relevance of the production function in regard of the more rigorous and general flow-fund model³⁷.

To sum up more generally, this section has provided us with a more elaborated view of the functions that a model may perform in Georgescu-Roegen's work. The two functions on which he insisted in his methodological claims are effectively put into practice with the flow-fund model. The model was used to check the logical consistency of certain aspects of older theories, those of Babbage and Smith, and to make more accurate and facilitate the understanding of the organisational patterns, through combinatorial results and graphical representations. But this led also to highlight some slightly different functions. First, by facilitating the understanding of these patterns, the model has a retroactive effect at the conceptual level which contributes to the formation of concepts by categorising situations. Second, by identifying the concept of production function as a specific configuration of the more general flow-fund framework, it enables to delimit its domain of validity and to check the conceptual relevance of various interpretations. While these results essentially concern the organisation of production processes at the micro level, the next section will explore the implications of the flow-fund model at the macro level.

2.3 Multiprocess models: from stationary state to evolution

In fact, once the elementary properties of a single process of production are established, Georgescu-Roegen turns toward the examination of the interrelation between processes at the level of a global economy. In order to represent formally this situation, he uses flow-fund tables such as table 1 (1971, p. 254). In this very simplified representation, P_1 , P_2 and P_3 are processes of production, N is the natural environment, and P_4 is the consumption process.

This step is very instructive with respect to Georgescu-Roegen's methodology of theory-making. First, it is intimately linked to the process of "isolation" of a relevant set of features. Indeed, the functional representation of production processes, at the core of the analysis at the micro level, is abandoned in favour of simple coefficients,

³⁷Nevertheless, this analysis of production processes has had only a limited influence on the economics of production. Some authors, for instance, have been interested in the divisibility and decomposability of elementary processes, and their consequences for the organisation of production Marzetti (2013). But obviously the neoclassical production function has remained dominant in the field.

Table 1: Economy E Represented in Process Form

	P_1	P_2	P_3	N	P_4
<i>Flow Coordinates</i>					
C_1	x_{11}	$-x_{12}$	$-x_{13}$	*	$-x_{14}$
C_2	$-x_{21}$	x_{22}	$-x_{23}$	*	$-x_{24}$
C_3	$-x_{31}$	$-x_{32}$	x_{33}	*	$-x_{34}$
R	$-r_1$	$-r_2$	$-r_3$	r	$-r_4$
W	w_1	w_2	w_3	$-w$	w_4
<i>Fund Coordinates</i>					
C_1	X_{11}	X_{12}	X_{13}	*	X_{14}
C_2	X_{21}	X_{22}	X_{23}	*	X_{24}
C_3	X_{31}	X_{32}	X_{33}	*	X_{34}
L	L_1	L_2	L_3	*	L_4
H	H_1	H_2	H_3	*	H_4

whose meaning is variable. In one place, we find that they are flows and services “over one year” (1971, p. 254), while in another one we find that all processes are assumed to be “factories operating continuously” and the coefficient are rates of flows and services 1976, p. 241. For the restricted case of factories both definitions are equivalent since the second one of coefficient is proportional to the first one. But the first one may also enable to consider activities that cannot be operated as factories but have a periodicity of one year, including most agricultural activities.

In both cases, Georgescu-Roegen operates a reduction of the subject matter relatively to the very general outlook initially adopted regarding production processes. As for the choice of considering that funds are unaltered by the production process, discussed in section 2.1, this isolation of a specific situation is associated to the framing of the kind of problems the theory will deal with. Here, we go from the issue of *internal organisation of processes* to that of *interrelations between processes*. And dropping the initial time-explicit feature of the flow-fund model appears as the price to pay to preserve “mental control” over the multiprocess model. Hence, once again the interpretation of Georgescu-Roegen’s methodological principles presented in section 1.2 is useful to make sense of these new assumptions.

The other element in this regard is that this table is supposed to represent a “stationary” economy. As for the categorisation of the different organisational patterns at the micro level, this notion emerges from two sources. On the one hand, at the dialectical level, it is an “idealisation” of a concrete situation where the economy reproduces itself from one year to another. But, on the other hand, it is also a secondary concept, in the sense that it is defined as a relation between the primary concepts of processes, flows and funds. Therefore, its understanding also relies in a more abstract way on the logical implications we can derive from these primary concepts thanks to the analytical model, where this situation is simply defined as the fact that the production of one commodity is equal to its consumption

in other sectors. Once again, the analytical simile contributes to the formation of new concepts integrated in the structure of the theory in a retroactive way.

Table 2: The Input-Output Table of Flows in Economy E

	P_1	P_2	P_3	N	P_4	Totals
C_1	*	x_{12}	x_{13}	*	x_{14}	x_{11}
C_2	x_{21}	*	x_{23}	*	x_{24}	x_{22}
C_3	x_{31}	x_{32}	*	*	x_{34}	x_{33}
R	r_1	r_2	r_3	*	r_4	r
W	$-w_1$	$-w_2$	$-w_3$	*	$-w_4$	$-w$

Moreover, this equality between production and consumption in a stationary state enables to relate his representation of production to the conventional input-output table introduced by Wassily Leontief. This is achieved simply by reorganising the flow coordinates and changing their signs in order to obtain table 2. In this sense, Georgescu-Roegen acknowledges that “the flow matrix and the input-output table are two completely equivalent forms”(1971, p. 255).

However, he also distinguishes his approach on a number of points. First, while “Leontief includes in the input-output table the ‘flow’ of labor services which he regards as the ‘output’ of the consumption sector”, he prefers to “abide by the fundamental difference between flow (as a substance that crosses a boundary) and service (as an action performed by a fund element inside the boundary)” (1971, p. 255, n. 66). Second, his main reproach toward input-output tables concerns the introduction of “internal flows”. An internal flow is represented by a positive coefficient on the diagonal of table 2, and especially appear after the consolidation of two processes, for instance P_1 and P_2 ³⁸. While Leontief initially suggested that this latter coefficient should be suppressed and the total modified accordingly, economists such as Dorfman, Samuelson and Solow later argued that it could be preserved as an internal flow of the consolidated process. But according to Georgescu-Roegen, this idea hides a conceptual flaw:

According to the analytical view of a process, however, flows are the elements that are especially associated with a crossing of a boundary. Consequently, once we have removed from our analytical picture [...] the boundary between P_1 and P_2 , gone also must be the flows associated with

³⁸If the consolidation procedure is performed on the flow matrix of table 1, we must add up the columns representing P_1 and P_2 to represent the consolidated process P_0 . This process will produce a commodity C_0 representing the aggregation of C_1 and C_2 , which also requires that the corresponding lines be added.

At the end of the procedure the output of P_0 will be $x_{00} = x_{11} + x_{22} - x_{12} - x_{21}$, and if the new flow matrix is transformed into an input-output table, x_{00} will appear in the totals column while the first coefficient on the upper left of the diagonal will still be zero. On the other hand, if the same consolidation is done directly on the input-output table 2, then $x_{11} + x_{22}$ will appear in the totals and $x_{12} + x_{21}$ will represent the internal flow on the diagonal.

them. Analytically, therefore, the term ‘internal flow’ is a mismatch.
(Georgescu-Roegen, 1971, p. 260)

We can make sense more accurately of Georgescu-Roegen’s argument based on the methodological principles identified in section 1.2. Indeed, relying on the example of a canal, Georgescu-Roegen shows that the value of the internal flow depends on how the internal boundary is drawn³⁹. Therefore, there is no way of defining the internal flow of the canal without an *explicit* boundary in mind. But if we have such a boundary at the dialectical level it should also appear at the analytical level, since the latter is supposed to assess the logical consistency of the reasoning based on the former. Hence, what is at stake here is the principle of structural consistency between the dialectical and the arithmomorphic levels, to which the step of arithmetisation must pay attention according to Georgescu-Roegen’s methodology.

Moreover, in a similar way to what he did regarding the production function, Georgescu-Roegen relies here on his analysis of production to highlight the shortcomings of input-output tables. Once again, the function of the model is not so much to check for logical errors than to check for conceptual ones. But while his main claim that a production function in quantities should involve time explicitly was wrong, in this case the criticism of internal flow seems perfectly relevant. Beyond this issue and the status of labour, the flow matrix of his representation is equivalent to Leontief’s framework. However, it adds to it the fund matrix, which plays an important role when dealing with prices and values⁴⁰.

The next important question is to understand how the structural features of the flow-fund table may evolve according to Georgescu-Roegen. In this respect, he introduces a distinction between growth and development, which he presents as one of Schumpeter’s legacies. According to this distinction, growth is a mere quantitative increase in the production with unchanged characteristics, while development is brought about by a qualitative change in the nature of produced goods and capital equipment. Schumpeter illustrated this distinction stating that you can “add successively as many mail coaches as you please, you will never get a railway thereby” (Schumpeter 1934, quoted in Georgescu-Roegen 1976, p. 243).

Following this idea, Georgescu-Roegen characterises his approach to economic development as “analytico-physiological”⁴¹. By this formula, he underlined that

³⁹Georgescu-Roegen supposes a canal with constant speed of flow. Hence, if the boundary crosses n times the flow of the canal perpendicularly, the internal flow is n times the speed of flow.

⁴⁰We should not deal with this last issue here. For a brief outline, Georgescu-Roegen examines Marx’s diagram of simple reproduction, considered as equivalent to an input-output table. He suggests that Marx’s main mistake regarding the transformation of values into prices is that he considered capital and labour as flows rather than funds. Then, he proposes his own solution to Marx’s problem thanks to the flow-fund model. See chapter IX, section 14 in Georgescu-Roegen (1971)

⁴¹This category is defined in opposition to two other: the “mathematico-imaginative”, by which he means models “erected on one or several assumptions having no operational value whatsoever outside the paper-and-pencil concatenation”; and the “mechanico-descriptive”, which encompasses theories that “reduce the essence of all phenomena to some motions” and “show no interest in going beyond the description of these motions” (1976, p. 235-236).

even though it relies on analytical relations, this approach insist on “the detailed manner in which the interrelations between the various components of the process under consideration are described” and “the particular attention paid to the qualitative change inherent in any actual process” (1976, p. 236). Understood as such, the analytico-physiological approach shares many features with Georgescu-Roegen’s methodology, and may in fact appear as a relevant label for the latter.

In particular, this point is tightly linked with Georgescu-Roegen’s criticism of the use of aggregated variables in macroeconomic models. As is now clear from table 1, in his model, capital is represented by different forms C_i , which “are not all qualitatively identical and, hence, have no common measure” (1971, p. 244)⁴². As a consequence, according to him, what is generally interpreted as substitution between factors of production in the neoclassical framework, implies in fact a qualitative change of the funds involved in the production process. For instance, he underlines that “a more capital intensive process normally requires a different type of capital”, and therefore, “there is no sense of speaking of the elasticity of substitution between homogeneous capital and homogeneous labor” (1971, p. 243-244). From this point of view, substitution appears as a misleading word to describe what is in fact a qualitative change of production processes.

The methodological principles at stake here are those of “idealisation” and “arithmetisation”. Indeed, on the one hand, following my interpretation of Georgescu-Roegen’s methodology, the fundamental elements of the theory should be conceived based on our intuitive identification of “sameness”. In this respect, aggregated capital does not make sense at the conceptual level, because it is not to any “commonsensible”. On the other hand, because of the principle of structural consistency between the dialectical and the arithmomorphic levels, these fundamental elements must appear as such in the model, even though the latter can only represent a partial view of the formers. Hence, the notions of homogeneous capital, homogeneous labour, and their by-products, such as elasticity of substitution or marginal productivity, do not have any meaning in this methodological framework. And this leads Georgescu-Roegen to break with some of the fundamental concepts of the neoclassical theory of production and distribution⁴³.

Moreover, this is a crucial feature of Georgescu-Roegen’s approach to economic change in the long run. Indeed, he suggests that the “inherent dependence on quality” of economic development “puts it well beyond the reach not only of the dynamic models, but of any other conceivable arithmomorphic apparatus” (1976, p. 245). By “dynamic models”, he especially aims at the growth models of Harrod, Domar,

⁴²Later, Georgescu-Roegen related his own opinion to the criticism of aggregated capital expressed by keynesian economists and agreed that “there are therefore plenty of reasons to say, with [Joan] Robinson, that ‘the Wicksteedian production function has been a powerful instrument of miseducation’ ” (1990, p. 207). Moreover, in Georgescu-Roegen’s perspective this may also apply to land and labour, even though it is not explicit in the simplified version of table 1.

⁴³This is also one of the foundations of Georgescu-Roegen’s criticism of the substitution between manufactured capital and natural resources. This kind of substitution was put forward in the first models of growth with exhaustible resources, especially those of Solow (1974) and Stiglitz (1974), as a mechanism that could offset the exhaustion of resources. See Couix (2018) for a detailed analysis of the related controversy.

Solow and Leontief. What he reproaches to these models is their reliance on a change in the structure of production, for instance an increasing capital intensity, which, in his opinion, is a qualitative change related to development rather than growth. And he insists that “if there is development, the systems that represent the processes during the successive growth periods refer to a continually changing spectrum of commodities” (1976, p. 248). Therefore, this is clearly the translation in the specific field of the economics of production of the distinction between “dynamics” and “evolution” found among his methodological principles in section 1.2. According to it, a dynamic perspective can only study quantitative changes, that is mere growth., while an evolutionary approach should pay attention to qualitative changes in order to understand development proper.

What does this tell us about the purpose of the flow-fund table of a multiprocess economy? As discussed above, Georgescu-Roegen underlines that the relation between the different factors of production is defined in very narrow limits. In this perspective, the flow-fund representation of a given process may only be used for dynamic purposes, that is when production processes stay the same. But, according to him, this situation is unable to explain the most important part of economic changes, in particular since the industrial revolution has brought about an increasing number of technological innovations. To understand these transformations, qualitative changes in the nature of production processes must be taken into account. This implies a structural modification of the flow-fund table, which will involve new output commodities, factors of production, and analytical relations between both. Hence, these changes cannot be accounted for by the kind of differential equations used in dynamic models, that necessarily rely on continuously defined variables.

In return, this enables us to question Georgescu-Roegen’s methodology, according to which the relevance of a theory is necessarily limited in space and time. Indeed, the flow-fund model is not presented as a representation of some local economic reality, but instead as a general and universal framework for the analysis of production. While this may appear contradictory with the methodological principle above stated, the paradox is removed by the indeterminateness of the general model, both in term of elements and relations, and the necessity of specifying these qualitative features for each concrete situation. Hence, Georgescu-Roegen’s methodology is best understood as an articulation between: an “abstract” level, both in terms of dialectical and arithmomorphic concepts, that must capture the general features of the issue considered; and a “concrete” level, where the framework is filled with some specific content⁴⁴.

In addition, this interpretation of Georgescu-Roegen’s methodological position

⁴⁴This analysis is essentially dedicated to the case of the theory of production considered here. However, it seems also consistent with the criticism Georgescu-Roegen addressed to the neoclassical theory of economic behaviour: “The statement that the fundamental principles of economics are universally valid, therefore, may be true only as their *form* is concerned. Their *content*, however, is determined by the institutional setting. And without this institutional content, the principles are nothing but ‘empty boxes,’ from which we can obtain only empty generalities. This is not to say that standard theory operates with ‘empty boxes.’ On the contrary, as we have seen, those boxes are filled with an institutional content distilled from the cultural patterns of a bourgeois society.” (1971, p. 324)

leads to think that the flow-fund model may mostly be used as a descriptive tool of the interrelations between some given production processes, corresponding to current technologies or to prospective situations. In this framework, long-term qualitative change may only be represented by successive technological states of the economy, but not by a unifying dynamic system between these different states. Hence, the evolution is never fully encapsulated in one mathematical model. Instead, this approach fits best with a methodology of scenarios, studying the features of different possible structures of the economy, without deterministic nor predictive ambitions. This seems a consistent interpretation of the idea that the analysis of economic change cannot “attain its aim through an arithmomorphic model *alone*” (1976, p. 237, italics in the original).

Conclusion

By the end of his life, in one of his last writings in which he was asked to speak about his “life philosophy”, Georgescu-Roegen recognised that although he had not been a “professional philosopher”, philosophical questions had occupied a prominent place in his economic thought. And he added that:

[Although] I have asked questions about things, their nature, and their relations among themselves and with the human mind, I have gone further: I have also asked questions about questions. (Georgescu-Roegen, 1992, p. 129)

In other words, he had a strong interest for methodology, and it is precisely this aspect of his thought that the present paper has intended to capture, make more intelligible and critically assess.

This has been done following two lines. First, his explicitly methodological claims were examined and connected with related topics in the contemporary literature on economic methodology. From this, his approach to theory-making has been summarised as a three steps process. This process starts with the “idealisation” of commonsensibles of the real world in the form of dialectical concepts, according to the principle of sameness and in the spirit of Weber’s ideal-types. This determines the temporal and geographical limits for the relevance of the theory, which is only intended to describe a specific economic reality, both at the cultural and material levels. The second step consists in the “isolation” of a limited spectrum of relevant features to form a dialectical reasoning. This sets a quantitative restriction intended to keep the reasoning under mental control, considered as the only control in social science due to the lack of measuring instruments. Last but not least, the step of “arithmetisation” provides an analytical simile of the dialectical reasoning. Because of the strong discrepancy between dialectical and arithmomorphic concepts, which is at the heart of Georgescu-Roegen’s philosophy, the latter can only partially represent the former and different representations are eligible. However, the arithmetisation must preserve the structure, that is there must be a one-to-one correspondence between the concepts at both levels. Moreover, at each and every step

there is a certain degree of looseness in Georgescu-Roegen's methodology, as himself acknowledges, and for which he refers to the "esprit de finesse" of Pascal or the "delicacy and sensitiveness of touch" of Marshall.

According to this methodology, the analytical simile performs two functions. First, it enables to check the logical consistency of dialectical reasoning, because of the rigour with which arithmomorphic concepts can be manipulated. This can especially be used to check for errors or validate theories of economists who reasoned only dialectically. Second, it is assumed to facilitate understanding, because of the simplicity with which it enables to follow deductive reasoning. Hence, the logic of the three step process above is that we loose in realism what we gain in understanding and logical consistency as we go along it, which best fits the idea of modelling as theorising developed in the philosophical literature on economic models. However, Georgescu-Roegen denies that a model can provide a tool to test the validity of the theory as a representation of reality. Contrary to the instrumentalist methodology, he believes that social sciences do not have objective standards of accuracy, such as those provided by measuring instruments in physics. He especially criticises the relevance of statistical tests in economics, which he considers as mathematical artifices. And finally, with respect to the idea of models as investigative instruments, Georgescu-Roegen's methodology is ambiguous. In particular, it is not clear whether or not it can be used for conceptual exploration, for instance by categorising and examining the features of specific configurations.

This kind of ambiguity is in fact one of the motivations for the second line of inquiry developed in this paper, which consists in confronting the construction of Georgescu-Roegen's flow-fund model of production, his most developed analytical contribution after the 1970s, with the methodology outlined above. Indeed, this part explores the issue in two ways simultaneously: from methodology to practice, and back. On the one hand, the above interpretation of Georgescu-Roegen's philosophy is used as a reading grid to make sense of the process by which he builds his theory of production. On the other hand, this process of theory-making gives the opportunity to learn about his methodology through the practice, revealing both its limits as a practical guide and complementary implicit principles.

This approach happens to be quite fruitful. To start with, it shows that the structure of the flow-fund theory of production can be interpreted in a very consistent way with respect to the methodology, while highlighting some new features of the latter. More precisely, the foundations of the theory rest on the concepts of "process", "boundary", "flows" and "funds". However, where Georgescu-Roegen's insist sometimes a lot on their analytical facet, I suggest that they are first and foremost idealisations based on an intuitive understanding of reality. The steps of isolation in turn appears when it comes to setting apart the qualitative change of funds in the process, and later to adopt a simplified representation of the multiprocess which puts aside the initial functional approach. In return, this teaches us that this step of the methodology is intimately linked with the kind of problem the model is designed to deal with, which goes here from the issue of internal organisation of processes to that of interrelations between processes. Finally, both at the micro and macro levels, Georgescu-Roegen's models are built in a structurally consistent way

with regard to the dialectical reasoning they attempt to represent. This appears most clearly in his insistence that flows and funds should not be represented by aggregated variables, which do not have equivalent in our sensible experience of the process of production. Moreover, this clarifies the kind of temporal and geographical limitations he assigns to models, which are then best understood as articulations between an “abstract” level, that must capture the general features of the issue considered, and a “concrete” level, where the framework is filled with some specific content.

As for the functions attributed to models, this investigation confirms that the two previously identified are effectively put into practice. On the one hand, the model was used to check the logical consistency of certain aspects of older theories, vindicating especially the “multiple principle” of Babbage and the relation between specialisation of tasks and the size of demand according to Smith⁴⁵. On the other hand, it was as well used to make more accurate and facilitate the understanding of the different organisational patterns. Combinatorial results and graphical representations were especially necessary to clarify the properties of the “in line” organisation associated with the factory system.

But this led also to highlight some slightly different functions performed by the model. First, by identifying alternative models with specific configurations of the flow-fund model, Georgescu-Roegen is able to check their conceptual consistency with respect to his own conceptual foundations. As a result, the production function may be interpreted both as a relation between quantities and as a relation between quantities per unit of time, but its domain of relevance is limited to activities that can be organised in line, which is not the case of agriculture in particular. Similarly, the notion of “internal flow” in input-output analysis is shown to be conceptually flawed according to the principle of structural consistency between the dialectical and the arithmomorphic levels.

Second, by facilitating the understanding, the model has a retroactive effect at the conceptual level which contributes to the formation of concepts. This leads to refine the structure of the theory by highlighting a second level of concepts, which are defined as relations between the primary concepts of process, boundary, flows and funds. These relations are partly conceptualised as idealisations of situations in the real world, and partly by the logical implications and understanding we can derive from their corresponding analytical representation in the model. This is the case for the categorisation of the different organisational patterns of a single production process, especially the “in line” organisation. But it is also the case for the “stationary” state of a multiprocess, which intends to capture both a concrete situation where the economy reproduces itself from one year to another and the analytical condition that the production of one commodity is equal to its consumption in other sectors.

Overall, this investigation underlines the important consistency between the methodological principles formulated by Georgescu-Roegen and his practice of theory-

⁴⁵While these examples are both derived from the representation of a single process, the representation of a multiprocess in turn was used to discuss Marx’s issue of the transformation of values into prices. However we didn’t deal in detail with this aspect.

making. But it also highlights their complementarity in mutually improving the understanding of his economic thought. However, an important aspect of the latter has been deliberately left out of this picture and should be examined further in later research: the role of natural resources in production and their relation to thermodynamics. Indeed, Georgescu-Roegen is well known for underlying that the physical facet of the economic process is intimately linked with the laws of thermodynamics. While this idea was formulated as a general principle, its consistency with the flow-fund theory is not obvious in his work. In many respect, there is a similar necessity of reconstructing the links between these two aspects of his thought as we have done for his methodology and his practice of theory-making. And of course, it should build on the lessons of the latter.

References

- Beard, T. R. and Lozada, G. A. (1999). *Economics, entropy and the environment: the extraordinary economics of Nicholas Georgescu-Roegen*. E. Elgar, Northampton (Mass.).
- Bobulescu, R. (2012). The making of a Schumpeterian economist: Nicholas Georgescu-Roegen. *European Journal of the History of Economic Thought*, 19(4):625–651.
- Chao, H.-K. (2009). *Representation and structure in economics: The methodology of econometric models of the consumption function*. Routledge, London.
- Cleveland, C. J. and Ruth, M. (1997). When, where, and by how much do biophysical limits constrain the economic process?: A survey of Nicholas Georgescu-Roegen’s contribution to ecological economics. *Ecological Economics*, 22(3):203–223.
- Couix, Q. (2018). The Role of Natural Resources in Production: Georgescu-Roegen/ Daly versus Solow/ Stiglitz.
- da Costa, N. and French, S. (2000). Models, Theories, and Structures: Thirty Years on. *Philosophy of Science*, 67:S116–S127.
- Düppe, T. and Weintraub, E. R. (2014). Siting the New Economic Science: The Cowles Commission’s Activity Analysis Conference of June 1949. *Science in Context*, 27(3):453–483.
- Friedman, M. (1953). The Methodology of Positive Economics. In *Essays in Positive Economics*. University of Chicago Press, Chicago.
- Georgescu-Roegen, N. (1935). Fixed Coefficients of Production and the Marginal Productivity Theory. *The Review of Economic Studies*, 3(1):40–49.
- Georgescu-Roegen, N. (1936). The Pure Theory of Consumer’s Behaviour. *The Quarterly Journal of Economics*, 50(4):545–593.
- Georgescu-Roegen, N. (1950). The Theory of Choice and the Constancy of Economic Laws. *The Quarterly Journal of Economics*, 64(1):125–138.
- Georgescu-Roegen, N. (1955). Limitationality, limitativeness, and economic equilibrium. In *Proceedings of the 2nd Symposium in Linear Programming*, volume 1, pages 295–330, Washington, DC. National Bureau of Standards.
- Georgescu-Roegen, N. (1960). Economic Theory and Agrarian Economics. *Oxford Economic Papers*, 12(1):1–40.
- Georgescu-Roegen, N. (1966a). *Analytical economics, issues and problems*. Harvard university press, Cambridge (Mass.).
- Georgescu-Roegen, N. (1966b). Further Thoughts on Corrado Gini’s *Dellusioni dell’econometria*. *Metron*, 25(1-4):265–279.

- Georgescu-Roegen, N. (1967). An epistemological analysis of statistics as the science of rational guessing. *Acta Logica*, pages 61–91.
- Georgescu-Roegen, N. (1969a). The Institutional Aspects of Peasant Communities: An Analytical View. In Wharton, C. R., editor, *Subsistence Agriculture and Economic Development*, pages 61–99.
- Georgescu-Roegen, N. (1969b). Process in farming versus process in manufacturing: a problem of balanced development. In Papi, U. and Nunn, C., editors, *Economic problems of agriculture in Industrial Societies*, pages 497–533. Springer.
- Georgescu-Roegen, N. (1970). The Economics of Production. *American Economic Review*, 60(2):1–9.
- Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process*. Harvard University Press, Cambridge (Mass.).
- Georgescu-Roegen, N. (1976). Dynamic Models and Economic Growth. In *Energy and Economic Myths: Institutional and Analytical Economic Essays*, pages 235–253. Pergamon Press, New-York.
- Georgescu-Roegen, N. (1990). The production process and dynamic economics. In Baranzini, M. L. and Scazzieri, R., editors, *The Economic Theory of Structure and Change*, pages 198–226. Cambridge University Press, Cambridge, UK.
- Georgescu-Roegen, N. (1992). Nicholas Georgescu-Roegen about himself. In *Eminent economists: their life philosophies*, pages 128–59.
- Halsmayer, V. and Hoover, K. D. (2016). Solow’s Harrod: Transforming macroeconomic dynamics into a model of long-run growth. *The European Journal of the History of Economic Thought*, 23(4):561–596.
- Hands, D. W. (2006). Integrability, Rationalizability, and Path-Dependency in the History of Demand Theory. *History of Political Economy*, 38(Suppl 1):153–185.
- Hausman, D. M. (2000). Realist philosophy and methodology of economics: what is it? *Journal of Economic Methodology*, 7(1):127–133.
- Hausman, D. M. (2007). Introduction. In Hausman, D. M., editor, *The philosophy of economics: an anthology*. Cambridge University Press, Cambridge, UK, 3rd edition.
- Heinzel, C. (2013). Schumpeter and Georgescu-Roegen on the foundations of an evolutionary analysis. *Cambridge Journal of Economics*, 37(2):251–271.
- Koopmans, T., editor (1951). *Activity analysis of production and allocation: proceedings of a conference*. John Wiley & Sons, New York.
- Koopmans, T. C., Tinbergen, J., Georgescu-Roegen, N., and Orcutt, G. H. (1952). Toward Partial Redirection of Econometrics: Comments. *The Review of Economics and Statistics*, 34(3):200–213.

- Kurz, H. D. and Salvadori, N. (2003). Fund–flow versus flow–flow in production theory: Reflections on Georgescu-Roegen’s contribution. *Journal of Economic Behavior & Organization*, 51(4):487–505.
- Lawson, T. (1999). What has Realism Got to do with It? *Economics and Philosophy*, 15(02):269–282.
- Lenfant, J.-S. (2012). Indifference curves and the ordinalist revolution. *History of political economy*, 44(1):113–155.
- Marzetti, G. V. (2013). The Fund-Flow Approach: A Critical Survey. *Journal of Economic Surveys*, 27(2):209–233.
- Mayumi, K. (1999). Embodied energy analysis, Sraffa’s analysis, Georgescu-Roegen’s flow-fund model and viability of solar technology. In Mayumi, K. and Gowdy, J. M., editors, *Bioeconomics and Sustainability: Essays in Honor of Nicholas Georgescu-Roegen*, pages 173–193. Edward Elgar, Cheltenham.
- Mirowski, P. (1989). *More Heat Than Light*. Cambridge University Press.
- Missemer, A. (2013). *Nicholas Georgescu-Roegen, pour une révolution bioéconomique*. ENS Éditions, Lyon.
- Missemer, A. (2016). Nicholas Georgescu-Roegen and degrowth. *The European Journal of the History of Economic Thought*, 0(0):1–14.
- Mitchell, W. C. (1925). Quantitative Analysis in Economic Theory. *The American Economic Review*, 15(1):1–12.
- Morgan, M. S. (2008). Models. In *The New Palgrave Dictionary of Economics*, pages 1–14. Palgrave Macmillan, London.
- Morgan, M. S. and Knuuttila, T. (2012). Models and Modelling in Economics. In Mäki, U., editor, *Philosophy of economics*, volume 13 of *Handbook of the Philosophy of Science*, pages 49–88. Elsevier, Amsterdam.
- Morroni, M. (1992). *Production process and technical change*. Cambridge university press.
- Mäki, U. (2012a). *Philosophy of economics*, volume 13 of *Handbook of the Philosophy of Science*. Elsevier, Amsterdam.
- Mäki, U. (2012b). Realism and Antirealism about Economics. In Mäki, U., editor, *Philosophy of economics*, volume 13 of *Handbook of the Philosophy of Science*, pages 3–24. Elsevier, Amsterdam.
- Ould Boye, I. (2014). *Quelques traits caractéristiques de l’émergence d’une "hétérodoxie" : le cas de l’économie écologique*. PhD thesis, Paris 1, Paris.
- Poirier, B. (2014). *A Conceptual Guide to Thermodynamics*. John Wiley & Sons. Google-Books-ID: XBUNBAAAQBAJ.

- Røpke, I. (2004). The early history of modern ecological economics. *Ecological economics*, 50(3):293–314.
- Scazzieri, R. (1993). *A theory of production: Tasks, processes, and technical practices*. Clarendon Press, Oxford.
- Schumpeter, J. A. (1934). *The Theory of Economic Development: An Inquiry into Profits, Capital, Interest, and the Business Cycle*. Harvard University Press, Cambridge, MA.
- Solow, R. M. (1974). Intergenerational Equity and Exhaustible Resources. *The Review of Economic Studies*, 41:29–45.
- Stiglitz, J. E. (1974). Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths. *The Review of Economic Studies*, 41:123–137.
- Vromen, J. (2012). Ontological Issues in Evolutionary Economics. In Mäki, U., editor, *Philosophy of economics*, volume 13 of *Handbook of the Philosophy of Science*, pages 737–764. Elsevier, Amsterdam.
- Weintraub, E. R. and Gayer, T. (2001). Equilibrium Proofmaking. *Journal of the History of Economic Thought*, 23(04):421.
- Wicksteed, P. H. (1894). *An Essay on the Co-ordination of the Laws of Distribution*. London School of Economics, London, 1932 edition, reprint no. 12 edition.
- Zamagni, S. (1999). Georgescu-Roegen on consumer theory: an assessment. *Bioeconomics and Sustainability: Essays in Honor of Nicholas Georgescu-Roegen*, pages 103–124.