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The use of modeling tools for policy in evolutionary environments

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ABSTRACT

This is a position paper on the possibilities of informing the (economic and environmental) policy debate by using quantitative evolutionary models. I argue that an evolutionary worldview implies that the existing quantitative modeling tools used for policy analysis are problematic. Then I summarize the main elements of an evolutionary way of analysis, and the way in which it can be incorporated into quantitative models. I conclude with an outline of a proposal for how to apply the ideas in the analysis of energy transitions.

1. Introduction

Evolutionary economics has been presented as a more relevant alternative to mainstream economics [1]. It is rooted in the economic analysis of technological change and innovation, and argues that it can provide a more realistic theory of these phenomena than the mainstream economics approach can. Since innovation is a societal process with wide-ranging impacts, evolutionary economics is potentially very relevant for policy.

But at the same time, the direct policy implications of evolutionary theorizing are far from clear. For example, it is not clear if the policy implications from evolutionary economics differ from those of mainstream economics. Even if the foundations of the two theories differ, the policy implications may be similar, especially when formulated at a general level ("stimulate technological innovation").

Policy advice by economists has traditionally been based on quantitative simulation models that can be used to 'predict' the effects of policies, as if it were a laboratory setting. This has the advantage that the impact of policies can be assessed ex ante in a precise way (at least, if the model's predictions are by-and-large correct).

This paper is concerned with the question whether such an approach is also possible in the evolutionary economics tradition. Is it possible to formulate quantitative evolutionary models that can be used to support policy? Given the tentative but affirmative answer to this question that I will give below, I will further ask whether the use of such evolutionary models differs from the use of the traditional economic policy models.

I will lay out my argument in the following way. In Section 2, I will briefly summarize the foundations of the mainstream economics approach to quantitative policy modeling. In Section 3, I will discuss the basic ideas of evolutionary economic analysis, and define what I consider the most important elements of evolutionary thinking for the question formulated above. Section 4 will discuss two particular approaches to modeling, i.e., the use of confidence intervals and scenario analysis, and their relevance for evolutionary policy modeling. Section 5 will present a list of more concrete guiding points for evolutionary policy models. Finally, this list will be used in Section 6 to briefly outline an approach to evolutionary policy modeling in transition analysis.

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2. Economic policy models and the notion of equilibrium

Economics has a relatively strong influence on policy thinking through the use of large-scale econometric models that are used for simulations to support policy. In these models, as in general in economics science, the notion of equilibrium plays a large role. The usual definition of equilibrium is that it is a state of the system in which none of the economic agents (firms, consumers) has an incentive to change behaviour (e.g., charge higher prices, or buy more of a certain good). Without such an incentive, there is no factor (apart from random fluctuations) that may induce any change, hence the term equilibrium. In such a *static* equilibrium, nothing changes in the way the economy works. Economic policy models are based on a notion of *dynamic* equilibrium. In its basic form, dynamic equilibrium is a sequence of static equilibria.

Take, for example, the case of a simple model of supply and demand. The interaction between demand and supply will lead to an equilibrium that is characterized by a unique price and quantity sold. As long as this equilibrium is not reached (i.e., the price is either too high or too low), buyers and suppliers have an incentive to change their strategy. If the price is too high, suppliers cannot sell all products they wish to sell. Hence there is an incentive for the suppliers to change their behaviour, for example by offering their surpluses at lower prices. This continues until the market reaches a point where demand and supply intersect, and none of the parties has an incentive to change behaviour. We have reached static equilibrium.

However, if some of the external (*exogenous* is the usual technical term) factors that determine the market outcome change, the nature of the static equilibrium changes. For example, if the supply curve in our market example shifts to the left (e.g., due to climatic circumstances), the equilibrium market price will go up and the equilibrium quantity will go down. The result is a *dynamic equilibrium path* in which the price goes up from one period to another, and the quantity goes down.

The economic policy modeling tradition that starts with Tinbergen is based on this framework of a dynamic equilibrium path. More specifically, it assumes that a) the dynamic equilibrium path is unique and stable, b) adjustment to static equilibrium is instantaneous, and c) we can calculate the equilibrium based on an empirical specification of the model that can be obtained by statistical procedures (econometrics). These three assumptions, which I will discuss critically in Section 3, enable the policymaker to compare a whole range of policy options by plugging them into the model, and interpret the outcomes in terms of various variables that are of interest for the maximization of policy outcomes. On the basis of such a comparison, the most favourable policy outcome can be selected, and the respective policy can be implemented [1]. Equilibrium is a cornerstone in this way of thinking, because it is an essential concept for the calculation of the effects of the policy variables. Changes in policy will change the equilibrium, and the measurable effect of policy is taken as the difference between those two equilibria.

The individual equations of the model that must be used to calculate the equilibrium are usually based on microeconomic theories of agent behaviour (this is the so-called micro-foundation of macroeconomics). For example, a supply curve will be based on a theory of producer behaviour (profit maximization) under restrictions set by market structure and production technology. In this step from micro to macro relations, the representative agent plays a large role. This is a notion that is used to aggregate outcomes of the microeconomic theory directly to the macroeconomic level, without the need to explicitly add up different behavioural patterns.

Uncertainty plays only a minor role in this approach. It enters the equations in the form of a random disturbance term (with very specific characteristics) that is added to each equation. Thus, it can be expected that the actual outcome that will be observed in the real economy differs slightly from the outcome predicted by the model, due to these random disturbances. But for policy analysis, the disturbances do not matter, since they do not affect the structure of model.

3. Evolution, equilibrium, policy, and modeling

Before I compare the above approach to a more evolutionary way of thinking, there is a need to define what is meant by such an evolutionary approach. Quite often, an evolutionary process is defined as one in which novelty and selection work hand-in-hand to produce change. Although this is obviously a correct, and often useful definition, I will not adopt it here. The reason is that many of the empirical studies in the neo-Schumpeterian tradition (e.g., [2,3]) do not start from the formal assumption of mutation and selection, but do, in the end, share the most salient outcomes of the formal evolutionary framework as in [1].

Instead, I define the following four crucial characteristics of a socio-economic evolutionary process. First, such a process is characterized by bounded rationality at the micro level, leading to significant variety of behavioural patterns. When faced with the same external environment, different agents (individual consumers, firms) may react in different ways, and show different behaviour. Note that this is in contrast with the mainstream assumption of a representative agent, which assumes homogeneous behavioural patterns.

Second, evolutionary processes are characterized by a certain degree of persistence of random events. In simple words, small random events may change the course of history. Rather than being additive to a deterministic equilibrium, small random events in evolutionary processes may accumulate into larger factors that may change the nature of the system and its history.

Third, if equilibrium plays any role in an evolutionary process, it is in the form of multiple equilibria. A dynamic system that has a single, stable equilibrium, will, at least in the long run, always tend towards this single equilibrium. This makes prediction simpler. But in an evolutionary context, there generally are multiple equilibria, meaning that which particular equilibrium state is

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[1] An additional problem is how the different variables (e.g., income growth, distribution, unemployment) should be weighted, but we will abstract from this here.

reached depends on where the system starts (or, to take an advance on our discussion below, where it is pushed, for example by policy).

Fourth, in any evolutionary system, the speed with which equilibria are approached may vary over time (so-called punctuated equilibrium), but always takes a non-trivial amount of time. Moreover, the equilibria themselves are not fixed, but are changing as a result of change in the system itself. As a result, equilibria in an evolutionary system are rarely actually reached. Instead, they serve as an attractor that pulls the system in a certain direction for a prolonged period, before giving way to a new attractor. The consequence of this is that we cannot take the 'equilibrium' of an evolutionary model as a useful description of an actual future state of the world. Instead, we must model the path towards the equilibrium as an approximation of what the world may look like.

Note that each one of these four characteristics may be found in non-evolutionary economic modeling approaches, but that only in a truly evolutionary economic model, the four are found jointly. For example, [4] uses the theory of bounded rationality and behavioural variety to model macroeconomic process, [5] makes extensive use of the notion of multiple equilibria, the notion of persistence of random factors is central in the econometric debate about unit roots [6], and the debate on convergence in living standards [7] puts strong emphasis on transitory dynamics towards dynamic equilibrium.

The result of these four characteristics of evolutionary processes is that that evolution is very difficult to predict. This does not only hold with regard to predicting in the time domain (i.e., saying something about the future), but also extends to the use of so-called "counterfactuals" in an evolutionary model [2]. In the biological/paleontological debate, this had led to the famous question (asked by Stephen Jay Gould) "What would be conserved if the tape were run twice" [9,10]. This question refers to the thought experiment in which we would be able to run two parallel worlds, initially similar to our own, in which evolution would take its course. After a significant amount of time had lapsed, would the two worlds look anything like each other, or like the one that we know now?

We can see how each of the four characteristics of evolution described above would contribute to producing widely diverging worlds. With bounded rationality, agents do not optimize globally, but instead implement small adaptive changes, of which there is a potentially wide variety. Which particular adaptive change is picked by an agent is hard to predict, and this implies a tendency to divergent evolution even when initial environments are similar. The persistence of random events will lead to an accumulation of incremental changes that is different in every realization of the stochastic process, again leading to different outcomes in the hypothetical parallel worlds. Multiple equilibria may equally fork the parallel worlds into different directions. Finally, when speed of the evolutionary change process differs between periods in each parallel world, this will induce again an element of difference between them. One would thus tend to answer that "not much" would be preserved if the tape were played twice. It seems impossible to predict which of these outcomes will actually prevail.

In such a situation, traditional methods of assessing risk may loose their relevance, since these are based on probability distributions. A probability distribution assumes both that the possible outcomes are known in advance, and that (an estimate of) a probability can be given for each. The weather is a good example of such a case: we all have a good understanding of which types of weather we can encounter on a specific location in a particular time of the year, and how likely these types are. But when uncertainty is strong, the possible outcomes are unknown, and the probability distribution cannot be conceived. An example from the early days of computers in the United States illustrates this well. According to by Katz and Philips (cited in [11]), the leading business men of the 1950s saw no commercial possibilities for the computer, which has been developed in prototype during the Second World War. They quote Thomas J. Watson Senior, CEO of IBM, as having expressed the feeling that "the one SSEC machine which was on exhibition in IBM's New York offices could solve all the scientific problems in the world involving scientific calculations", and hence there was no market for producing and selling computers. This view proved quite wrong, which illustrates how difficult it is to make predictions about technological evolution. The same T.J. Watson, by the way, quickly led IBM into leadership in the global computer industry in the 1950s.

Despite this strong level of uncertainty, there must be some bounds to evolutionary outcomes, if only because of the laws of nature (which, at a higher level, may be subject to evolution themselves). Thus, evolution is a process in which the two factors of 'chance and necessity' [12] are intermingled and determine the direction that a system takes. In evolutionary biology (see, e.g., the popular works of Dawkins and Gould), there seems to be some consensus that the chance side of this relationship is dominant, but I will argue below that the balance may be different in socio-economic evolutionary systems.

These characteristics of evolutionary processes largely invalidate the approach in building economic policy models that I discussed in Section 2. Bounded rationality and the associated behavioural variety invalidate the idea of a representative agent, and hence makes the usual aggregation procedures impossible. Multiple equilibria invalidate the calculation of the single equilibrium that varies under policy variations, and introduces the need to consider starting conditions and define basins of attraction. The effects of stochastic processes and uncertainty invalidate the idea of a unique and calculable equilibrium. Finally, the importance of transitory dynamics detracts from the importance of the equilibrium notion itself.

Although it is obviously possible to discuss these issues at greater length, I will not do so here. Instead, I will focus the largest part of the essay on the positive implications of these four evolutionary principles for policy modeling.

4. Evolutionary analysis and existing modeling traditions

The main challenge to building evolutionary policy models is the fact that evolution is a process in which chance plays a significant role. The key feature of evolution is that small, random (and therefore unpredictable) events may have severe long-run consequences. This means that any simulation exercises performed with a policy model must be taken with extreme caution.

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[2] See [8] for a much more elaborate discussion of the use of counterfactual history in evolutionary economics than is possible here.

In this section, I ask the question whether any existing ways of dealing with uncertainty in quantitative models can help us deal with this feature of the evolutionary process. Two specific issues come to mind: first, sensitivity analysis and the augmentation of model simulations with confidence intervals and standard errors, and, second, scenario studies.

Initially, the outcomes of the policy models as described in Section 2 were taken as point estimates, i.e., the specific dynamic equilibrium path that was produced by the model for a given set of policy parameters, was taken as the direct estimation of the impact of the proposed policy. This obviously does not consider the uncertainty that is embedded in these models. There are at least two sources of such uncertainty: potential parameter variations, and imperfect estimations of exogenous variables (including the variables related to the policy itself).

However, given that we have some information on the potential amount of (stochastic) variation in these two dimensions, we may actually produce not only the single dynamic equilibrium paths, but also produce an indication of how variable they are under reasonable stochastic variations. Hence, instead of using the parameter values obtained in econometric estimation, we may vary the parameters by using the standard errors of these estimations. Similarly, we can undertake sensitivity analysis of the model outcomes as a result of variation in exogenous (policy) variables. In this way, instead of a point estimate of the policy effect, we can obtain a confidence interval.

While confidence intervals are obviously a step forward compared to point estimates, they do not solve any issues related to the model structure itself. For example, a model that is based on the notion of a single equilibrium and traditional economic reasoning, does not change in nature by having it produce confidence intervals instead of point estimates. If the structure of the model and the main ideas underlying it is flawed, a more sophisticated sensitivity analysis will not rescue its predictive power.

Scenario analysis may be a more sophisticated tool of analysis that comes closer to the core evolutionary ideas. Scenario analysis is usually associated with the systems dynamics way of modeling [13], but it is also used in more mainstream (economic) policy models such as those used by the Netherlands Bureau of Economic Policy Analysis. In scenario analysis, an existing policy model is used to generate a number of outlooks on the future. A scenario is specified as a combination of specific assumptions that can be associated with a broad narrative about potential ways in which the system that is being modeled will develop. It is not the intention of the scenario analysis to predict which scenario will take place, and this is a major difference with the mainstream policy models discussed in Section 2.

Instead, the aim of scenario analysis is to explore the variety of potential outcomes under alternative assumptions. For example, in a model of the global (macro) economy, one may wish to investigate the general effects of different scenarios for the development of world trade. Then, one could specify one scenario in which world trade will stagnate, and one scenario in which international trade will grow. One may then investigate how a range of variables (e.g., global income distribution, CO_2 emissions, etc.) will differ between the scenarios. In this way, an impression is obtained of how whether or not world trade will grow will change the world.

Scenario analysis is less pretentious in prescribing specific policies than the models we discussed in Section 2. It gives insight into the available range of policies and the order of magnitude of their effect, rather than analyzing the exact impact of a specific policy. In this sense, it is closer to the principles of evolutionary systems as outlined above, because it recognizes the large degree of uncertainty present in the real world.

Although scenario analysis may certainly be useful, I maintain that, as a potential centerpiece of evolutionary model building, it is not very useful. As I will argue below, evolutionary models may well be used to conduct scenario analysis, and this is likely to add insights, but scenario analysis is not the saviour of evolutionary model builders. The reason for this is that at the heart of the models that are used for scenario analysis, we still have the same approach that is used to build the policy models I discussed in Section 2. If the model itself is not built on evolutionary principles, using it for scenario analysis does not make it evolutionary.

On the other hand, one may ask the question how the use of an evolutionary model may enhance the usefulness of sensitivity analysis and scenario analysis. In other words, will sensitivity analysis and scenario analysis be more useful in evolutionary policy models than in mainstream policy models? This question is hard to answer at this stage, since I have not outlined yet the features that, in my view, are salient for evolutionary policy models. As an advance to this discussion, let me state that both scenario studies and sensitivity studies may have much to gain from evolutionary foundations in the underlying model. In the case of scenario analysis, I think that an evolutionary approach may help to outline the source of different outcomes between scenarios (e.g., multiple equilibria). In the case of sensitivity analysis, evolutionary foundations may help to clarify the theoretical background of why confidence intervals appear the way they are.

5. Towards evolutionary policy models

Although, as argued above, we must be pessimistic about the possibility of existing risk-treatment techniques in quantitative policy models for dealing with “evolutionary uncertainty”, the prospects for using quantitative model tools in evolutionary policy analysis are not hopeless. This section will attempt to outline some possible ways of proceeding in this way. The key issue is about the mix between chance and necessity in the evolutionary processes that we wish to analyze for policy. What is the relative contribution of chance and necessity to evolutionary processes remains a matter open to debate. Arguably, the outcome of this debate will differ between pure biological and socio-economic evolutionary systems.

In biological evolution, the main source of novelty is random genetic mutation. Genetic mutation consists of errors in copying genetic information, and can be characterized as a truly blind process. Any specific genetic mutation that occurs in the history of a biological process may or may not lead to a “useful” design change, but whether or not the change is “useful” plays no role at all in generating the mutation itself.

In socio-economic systems, more complicated sources of novelty exist. An important source is behaviour of the micro-entities in the system (let's say firms and consumers). This behaviour, although not fully rational in the sense of mainstream economics, certainly has a purpose (as conceived by the agent). Behavioural change is implemented for a reason, and in general terms we may say that this reason is to generate better performance of the agent who implements the change. In addition, while genetic mutations are memory-less (there is a positive probability that a copying error is reversed later on), socio-economic agents have the ability to learn on the basis of their previous experiences. This opens up the possibility of experimentation aimed at finding a "good" strategy.

This has important consequences for the outcome of the evolutionary system. In the first place, the non-purposeful mutations in biology have a far greater potential range of impacts than the purposeful changes in socio-economic behaviour. Of all possible changes in behavioural patterns, the conscious economic agent will immediately rule out a number as non-sensible (even if they might make sense beyond the decision horizon of the individual agent). Biological evolution does not, at the level of the mutation itself, include any such selection. Thus, novelty in socio-economic evolutionary systems will be confined to a narrower (but possibly still rather broad) range than in biological systems.

Second, because agents in socio-economic systems can learn, as well as apply selection at their own micro level, the speed at which evolution may take place will be much higher than in biological systems. In other words, the relevant time horizons in socio-economic systems are much shorter than those in biological systems. The emergence of mankind took millions of years, the emergence of the Industrial revolution several decades.

These two differences between biological and socio-economic evolution have consequences for the nature of the two evolutionary processes. In biological evolution, the potential for predicting which direction evolution will take is an impossibility. Carbon-based life on earth is a "magnificent accident" indeed, and we should not expect something even broadly similar to emerge in a parallel world. But in socio-economic evolution, the range of directions that evolution may take may be smaller.

This does not imply that predictability of socio-economic systems is perfect, or even close to the level that is assumed by the policy models discussed in Section 2 above. Socio-economic evolution remains a historical process in which contingencies play a role. It is different from a mechanistic process with perfect predictability. Socio-economic evolutionary processes are somewhere in between the clockwork world of Newton and the magnificent accident of Stephen Jay Gould.

Where exactly the systems that we are interested in are on this continuum, depends on the scope that we are taking, both in terms of time (how long do we want to look ahead?), and the range of phenomena we wish to look at. Contingencies and random factors are more likely to play a decisive role in making outcomes of evolutionary processes indeterminate when we look either at large-scale systems of many interconnected components, or when we look at small-scale (micro) systems.

In the case of large-scale systems, indeterminacy is large because each of the interconnected components itself is unpredictable. Because of the dependency between the components in the system at large, unpredictability multiplies at the system level. The scope for building a precise quantitative evolutionary policy model for problems that require such large-scale systems analysis is thin.

At the micro level the problems are of a different nature. They stem from two sources. First, at the micro level, we have a large amount of external factors, each of which is the result of the large-scale system that we have discussed above. Second, behavioural patterns at the micro level are subject to a large degree of heterogeneity, and evolutionary theory as such does not have much to add about the way in which this heterogeneity can be analyzed. This is the domain of psychology, and possibly sociology or even (mainstream) microeconomics.

This leads me to a first conclusion on the nature of evolutionary policy models, and that is that they are most fruitfully applied to phenomena of 'intermediate range' [14]. When and if we can formulate problems that can be analyzed in an evolutionary system in which not too many different domains of interaction are involved, the scope for using quantitative models for policy purposes are good. What exactly is an "intermediate range problem", is hard to specify in general terms.

A sufficient but not necessary condition for an intermediate range problem can be formulated using the notion of multiple equilibria. If a specific policy problem is characterized by a small, but larger than one, number of equilibria, that can be clearly separated from each other, we may characterize this as a typical problem that can be modeled by evolutionary dynamics. Typically, problems in the field of transition analysis, e.g., environmental-friendly technological trajectories, can be characterized in this way (see, e.g., [15] for applications of modeling tools using multiple equilibria in ecological problems, and [16] for a model on electric vehicles that starts from the multiple equilibrium notion). I will therefore attempt to sketch the steps in modeling such transitions using evolutionary dynamics in the next section. Before doing so, however, I will formulate in the remainder of this section a number of general issues regarding the nature of evolutionary policy models.

In a pure technical sense, evolutionary models differ from more mainstream models in at least three ways that are important for policy analysis. The first one is the existence of multiple equilibria, the second is the importance of variety in behavioural patterns, and the third one is the normative interpretation of the model outcome or equilibrium.

Multiple equilibria provide a different perspective on policy than the one that is found in mainstream policy models. As summarized in Section 2, the usual way of looking at policy analysis in quantitative models is to assume that policy may change the nature of the (single) equilibrium in the model (world). With multiple equilibria, this is different. In addition to policy changing the character of the equilibria, there is also an option to move the system out of the basin of attraction of one equilibrium, and into that of a different one.

This is a significant change of perspective in several ways. For example, it is not so clear that the "Lucas-critique" is valid in the same way in the case of a world with multiple equilibria. Lucas [17] argues that if economic agents have rational expectations, government policy may in many cases be inefficient, because agents calculate the effects of government policy, adjust their actions accordingly, and the effect of the policy may be counteracted by this. In a technical sense, the equilibrium of the model is the same whether or not government policy is implemented. But if there are multiple equilibria, the response of the agents to government policies may leave the equilibria unchanged, but may still put the economy on a track towards a different equilibrium.

Also, if there are multiple equilibria, government policy has more options. If, for reasons of efficiency of policy instruments, some policies are not effective, other options may still be open. For example, it may be the case that the nature of each of the multiple equilibria depends on technology (e.g., the case of alternative energy systems), but government has insufficient information to select the agents that are best situated to advance a certain technology (this is the argument often used by those who oppose a government policy based on "picking winners"). In this case, policy may be geared towards bringing the system in the basin of attraction of a different equilibrium, without having to pick winners (i.e., specific firms to subsidize) within or between alternative technologies. Instead, a general policy aimed at stimulating consumption may do the trick.

Thus, an evolutionary policy model must take the existence of multiple equilibria serious. But it is hardly to be expected that a generic model (i.e., a set of equations that can be run on a computer) will tell us how many and which equilibria exist for a specific policy situation of interest. This is a task for exploratory analysis that must be performed before any particular model can be built.

This 'treatment' of multiple equilibria has two implications. First, it reinforces the argument about evolutionary policy model being theories of the intermediate range. We cannot build a generic model of the multiple equilibria that may attract the economic development of our society at large. We can only hope to build a model of the multiple equilibria of a problem in the intermediate range that we have carefully outlined by non-quantitative analysis before attempting to build a policy model.

Second, it implies that evolutionary model builders must work in close association with experts in a particular field, as well as experts in different kinds of (technology) foresight studies. This includes interacting with, for example, technical experts that work in a quantitative engineering tradition and who can help outlining the technology options, as well as using the heterogeneous 'art' of foresight studies in all its guises. The 'roadmaps' that foresight studies can produce should not be taken literal, but they can help in outlining in a general sense the various equilibria that serve as attractors in a socio-economic evolutionary system, as well as the factors that play a role in bringing the system towards one of these basins of attraction.

The second specific technical issue addressed by evolutionary (policy) models is behavioural heterogeneity, as it is implied by bounded rationality. I have already argued that it is not the domain of evolutionary analysis to specify theories of individual behaviour. Instead, evolutionary theories take the population perspective, i.e., they describe the various types of agents that can be found in a population, and the way in which their behaviour may change under the pressure of selection and the generation of novelty. In this way, evolutionary theories and models are related to the multi-agent simulation approach (e.g., [18]) or agent-based simulation approach (e.g., [19]).

There are two principal sources of behavioural variation in a population. The first is different characteristics between members of the population. Firms may differ in such dimensions as size, the products they produce, the technologies they use, their location, etc. Consumers may differ with regard to income, their preferences, their physical characteristics, etc. Such differences may induce differences in behaviour. The second source of behavioural variety lies in the notion of bounded rationality. Each individual agent may react differently to similar incentives, even in comparable circumstances. Exactly because individual behaviour is not completely rational (in the neo-classical economists' way), it is rather unpredictable, at least when analyzed from a population perspective.

In actual practice, these two sources of behavioural variety will interact, and it is difficult, if not impossible to separate them in terms of the empirical data that we have available. This is in strong contrast with the theoretical work in evolutionary economics, which has, traditionally since Nelson and Winter [1], focused on the side of bounded rationality as a source of variety. This focus is at least partly the result of a desire of evolutionary economists to differentiate themselves from neo-classical economists. Critique of the assumption of strong rationality in mainstream neo-classical economics is obviously a cornerstone of evolutionary economic theory. Thus, the existing evolutionary economic models, without a single exception, put a lot of emphasis on variety between agents that results from agents using different rules of thumb, or other decision rules. Variety that is related to differences in agents' characteristics has attracted much less attention.

In my view, this is a tendency that, although it may have merits in a theoretical context, is not very useful for the type of evolutionary modeling exercise that I propose here. In the intermediate range empirical model that I propose, we must arrive at a single, or at most a few, aggregate behavioural patterns by aggregating variety at the micro level. In order to be able to aggregate, we need both detailed data on the differences in characteristics in the population, and information (or an assumption) about variety in behavioural patterns (bounded rationality). In this aggregation process, the idea of fully modeling bounded rationality at the micro level is not very useful, for at least two reasons. The first is that the question of what motivates and drives an individual agent is, in most cases, simply not relevant for the more aggregate population-level outcome, what is relevant at the population level is that behaviour is heterogeneous. The second is that, under many circumstances, it will be impossible to specify bounded rationality in a different way than by exogenously specified varieties of 'rules of thumb'.

As a way out of this, I propose two potential solutions. The first is that we use micro level (evolutionary) theories to specify a limited number of "archetypal" patterns of bounded rationality, and link these to different population "scenarios" in the overall model. As an example, one may derive from a detailed (psychological) theory of consumer behaviour a taxonomy of consumers into "early and late adopters" (a real-world example would probably have a slightly more sophisticated classification), and link these to a specific fraction of the population to arrive at scenarios for overall population behaviour. Also experimental economics may be relevant for deriving and testing these behavioural patterns [20].

A second approach, however, may exist in simply using a single and rather straightforward assumption about actual bounded rationality in the population. This approach puts less emphasis on bounded rationality as a source of variety, and, instead, relies more on individual characteristics to generate the population diversity. When the single assumption on bounded rationality involves a (stylized) notion of optimizing, this strategy might appear as somewhat alien to the idea of evolutionary dynamics. Nevertheless, I argue that, if properly combined with variety in the characteristics of the population members, even such a simplified 'optimizing' approach can be useful at the level of intermediate range evolutionary models (see, e.g., [21] for an example of such a model). Specifically, in the example of a modeling strategy that I will discuss in Section 6 below, I will proceed along these lines, and use an explicit (although short-run) maximizing strategy for the population of adopters in the model.

Either way, these strategies depend to a large extent on the population variety that is generated by different characteristics in the population. Thus, there is, again, an important role for preliminary exploratory research. In this case, this must be aimed at describing, depending on the specific policy problem at hand, the user population, the way in which they may be affected by various factors in the model, and they way in which they may contribute towards moving the economy between equilibria. It can easily be seen that this requires different inputs than the type of foresight studies mentioned above. In this case, statistical information on user populations, as well as psychological, sociological and economic theory is needed to provide an adequate input to the model [3].

I finally address the issue of the normative interpretation of the model outcome or equilibrium. The mainstream economic approach starts from the model of perfect competition, which argues that the free market will lead to an optimal economic outcome (it maximizes welfare). Because in reality, some of the assumptions of the perfect competition model are not valid, we may encounter market failure, i.e., the free market produces a sub-optimal result. The implication is that policy should be aimed at restoring the optimum, i.e., correct market failure. Although there may be problems in calculating this optimum, and hence of implementing the right policy, the idea is that policy should somehow lead to a welfare optimum, and hence that the welfare optimum is a key criterion in evaluating policy.

Instead, in an evolutionary process, there is no clear goal to which the system will move. Evolution does not have a specific goal in the form of a global welfare maximum, even if in some sense evolution may maximize the degree of adaptation of a set of agents to its environments. Thus, even if an evolutionary system will tend towards some attractor, such an attractor does not have the normative implication of the mainstream welfare optimum. This implies that an evolutionary policy perspective will not evaluate policies by means of a welfare optimization criterion. Hence an evolutionary policy maker has a greater degree of liberty to pursue a range of options, and there is scope for policymakers to include subjective elements into the policy. For example, environmental policies may be implemented without arguing about welfare optimization.

6. Some specific ideas on the modeling of transitions

In this section, I will reflect on how the ideas expressed above can be put into practice in terms of developing an actual evolutionary model aimed at supporting policy decisions in the field of environmental analysis, more specifically problems related to transitions towards alternative energy systems, such as a hydrogen economy [22]. A secondary question is which particular policy measures can be envisaged to facilitate such transitions.

The general way in which I will attempt to tackle this, keeping in mind the ideas expressed above, is to formulate the policy problem as one that typically fits the intermediate range for which evolutionary models can be used, and then to apply the principles of evolutionary analysis, such as a population approach and the idea of mutant strategies. In general, this approach will imply that we collect and use a lot of specific information about the (future) hydrogen economy, rather than treating it as an abstract vision that can be characterized by a set of general equations.

6.1. Problem conceptualization

The set of factors that determine energy production and use can be characterized as a large-scale techno-economic system [23], with many complementarities. There are several factors that induce path-dependence in these systems. The first is that large-scale specific (infrastructural, but also tacit, e.g., in terms of knowledge) investments are necessary to support the system. A single actor is usually not able to finance these investments. Once in place, these investments represent a vested interest of the established players, which makes them less willing to switch to other technological trajectories. For a system that is challenging the vested interested (e.g., hydrogen), the large-scale investments represent a financial hurdle that is hard to overcome.

The second factor that induces path path-dependence is the fact that technological progress inside the system is strongly related to learning-by-doing and learning-by-using (i.e., dynamic increasing returns to scale, e.g., [24]). Hence new systems necessarily have to start at relatively low levels of productivity. Only by actually being implemented and used can productivity of the system grow. But with a more mature system in place, a new system may never reach levels of productivity that are competitive vis-à-vis the established system.

Theoretical work on competition between these technological systems has been presented in, among others, [25] and [26]. Models representing these processes have usually been formulated as dynamic models with multiple equilibria (e.g., [27]). Each technological system is represented by one equilibrium (path). Depending on where the system starts, it locks-in to one of these equilibria. Once the lock-in has occurred, it is hard for the system to select a different equilibrium.

Thus, the specific problem area that I have chosen can be seen as one of multiple equilibria, lock-in and competition between (large-scale) technological systems. I have argued above that such a situation of multiple equilibria is a potentially good case of an intermediate range problem that can be successfully tackled by evolutionary models. I will consider the specific policy problem as one of potential transition from the current mode of energy production and use, towards one in which hydrogen and fuel cells play the central role. Obviously, this context is closely associated to current debates in environmental analysis and policy. A large body of existing literature exists on this topic, much of which is applied to the specific Dutch policy context (e.g., [28–30]).

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[3] The emphasis on population dynamics in evolutionary models suggests a novel element in policy models in the form of evolutionary game theory. This is an interesting topic, but I will leave it unexplored here.

6.2. Preliminary field work

As I have argued above, I see an important task for technology foresight studies, as well as a general engineering understanding of a particular technology in the modeling process. The main purpose of this type of analysis is to outline the possible configurations of the equilibria in the process that is being modeled. This includes both the existing energy system (based on fossil fuels) and the system of which we wish to investigate the probability of transition, i.e., the hydrogen economy.

It is obviously beyond the scope of this paper to present a complete assessment of this type. I will therefore suffice by giving some general conclusions that this preliminary analysis could yield. Three major factors about which we need to form some kind of foresight in order to characterize the equilibrium development path of the current energy system based on fossil fuels, are the effects of scarcity of fossil fuels, the expected benefits (mainly in terms of CO_2 emissions) of technological innovation, and the societal attitude towards CO_2 emissions and the greenhouse effect. These foresights must be operationalized into three model variables/parameters: e.g., the future development of oil prices, the expected rate of reduction of CO_2 emissions in the use of fossil fuels, and the expected social pressure towards reducing CO_2 emissions.

For the hydrogen energy system, a detailed outline of technological possibilities and the technological efficiency that can be expected for each of them must be constructed using foresight techniques. This will generally imply that very specific information for various paths within the hydrogen economy is needed. For example, for the case of using fuel cells for micro cogeneration, and based on an outline of foresight studies, [28] distinguished different technological options, leading to a limited number of so-called technological clusters. For each of such technological clusters, a number of parameters, such as technologically efficiency, specific infrastructural costs, etc. are to be formulated. Obviously, since this is essentially a foresight analysis, the parameter sets must take into account variability of these expectations and investigate the sensitivity of the outcomes for this variability.

A different part of the model for which detailed data must be collected is the (potential) user population. The basis of this part of the model could be an analysis of the willingness to pay for the use of the new technology in various segments of population of the potential adopters. This can be based, e.g., on existing data on transportation patterns and expenditures (in the case of using hydrogen in cars), as well as projected population growth and policies. Again, variability in the projections is important.

6.3. Model elements and a general impression of results

A model constructed along these lines will consist of a set of technological options that can be chosen by the potential adopters, as well as a set of rules that govern the adoption decisions in the population of potential users. These adoption decisions ideally reflect various dimensions of the decision process, e.g., a comparison of the costs of using hydrogen and fuel cells relative to traditional energy systems, as well as risk associated with each system.

In a first stage of model building, these blocks, once they are empirically implemented, can be used to explore the multiplicity of equilibria in the model. In first instance, this will be an open process, in which one may expect a range of possible outcomes, e.g., a simple one equilibrium situation (the hydrogen economy never takes off), two equilibria (if the learning curve for fuel cells exceeds a certain threshold steepness, the hydrogen economy takes off), or a continuous range of equilibria (hydrogen will supply $x\%$ of total energy, where x is a continuous function of the learning rate in fuel cells).

As I have argued extensively above, the evolutionary interpretation would be most consistent with the second of these possibilities (i.e., two, or slightly larger number of equilibria). But there are no general criteria that will yield such an outcome, and I imagine that the second stage of model building would be aimed at interacting the model's outcome with those of the various foresight studies to determine if such a “limited number of equilibria” outcome is likely. If it is deemed to be so, the evolutionary model building process can enter its next stage, which is to clearly outline the various equilibria and the circumstances in which they occur (i.e., identify the basins of attraction).

Once this is done, the model may be used to evaluate policy, for example in the form of a number of standard scenarios, each one leading to a different equilibrium. The trial-and-error generation of such scenarios will provide insight into the working of various policy instruments. However, in line with the discussion above, we cannot take these results as predictions of what happens in the real-world evolutionary system in which the transition towards a hydrogen economy may (or may not) take place. We should take them as broad indications of the feasibility of a ‘hydrogen-equilibrium’ in the context of the multiple equilibria energy sub-system of the global economy. Rather than the end-result of a modeling analysis, they should be taken as the beginning or a more elaborate process of policy analysis.

A model formulated along these lines would not have to be an extremely realistic description of the actual evolutionary system of energy transitions, exactly because it would not be intended to be used in predictions (as many of the policy models based on mainstream analysis are). The main issue would be that they have to be transparent in explaining how they apply the evolutionary principles that I have outlined, i.e., the existence of multiple equilibria, the modeling of the user side by means of a population approach in which heterogeneity plays a major role, and close interaction between the model and more qualitative foresight techniques (i.e., the use of detailed information about technological and other forecasts). With this transparency, users of the model could explore alternative implementations of the main assumptions, thus building up a repository of model outcomes under alternative formulations (this resembles an open source approach).

With the help of such a repository, the potential diffusion of a large technological system like the hydrogen economy could be analyzed under a wide variety of circumstances. The results of this could be particularly helpful in judging the general feasibility of the hydrogen economy, identifying which aspects of the problem need most policy attention, and also to provide ideas about which policy instruments could potentially be effective.

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