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Landscape and flux theory of non-equilibrium open economy

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ABSTRACT

The economy is open and never in true equilibrium due to the exchanges with outside. However, most of the quantitative studies have been focused on the equilibrium economy. Despite of the recent efforts, it is still challenging to formulate a quantitative theory for uncovering the principles of non-equilibrium open economy. In this study, we developed a landscape and flux theory for non-equilibrium economy. We quantified the states of economy and identify the multi-stable states as the basins of attractions on the underlying landscape. We found the global driving force of the non-equilibrium economy is determined by both the underlying landscape gradient and the curl probability flux measuring the degree of non-equilibriumness through the detailed balance breaking. The non-equilibrium thermodynamics, the global stability, the optimal path and speed of the non-equilibrium economy can be formulated and quantified. In the conventional economy, the supply and demand usually has only one equilibrium. By considering nonlinear supply–demand dynamics, we found that both bi-stable states and limit cycle oscillations can emerge. By shifting the slope of demand curve, we can see how the bi-stability transforms to the limit cycle dynamics and vice versa. By parallel shifting the demand curve, we can also see how the monopoly, the competition, and the bistable monopoly and competition states emerge and transform to one other. We can also see how the mono-stable monopoly, the limit cycle and the mono-stable competition states emerge and transform to one another.

1. Introduction

In equilibrium economy, the interplay and balance between supply and demand becomes the key. The corresponding models have been widely used to illustrate how the balance of the price from the demand and production supply is determined. Demand is determined by many factors such as price, expected price, government policies, income level, advertisement, numbers of consumers etc. Supply is determined by also many factors such as price, price of other related products, expected price, government policies, cost and technology etc. A static single equilibrium can often be achieved for price when the supply and demand reach the balance. When the supply and demand change, the effects on the dynamics of the price and production quantity are usually described by the dynamical analysis based on the shift of the single equilibrium.

The "invisible hand" suggested by Adam Smith [1] can efficiently allocate resources in many free markets. The concept inspired Leon Walras to establish the existence of competitive general equilibrium for economy with linear supply and

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demand function [2]. Then Pareto defined optimality and established the coexistence of optimality and Walrasian general economic equilibrium. The theory was carried forward and extended [3,4].

Some economists have recognized the possibility of multiple equilibria for the partial equilibrium case in early times [2,5]. Such cases can give stable and unstable equilibria. In particular, Marshall considered that there can be an alternate tendency between stable and unstable equilibria. A small shift in a parameter can lead to a very significant change or transformation. As a result, the system can jump from mono-stable equilibrium to another one quite far away through an unstable equilibria. Furthermore, the idea of multiple oligopoly equilibria was also emerged. Joan Robinson first considered the pure monopoly case due to the possibility of upward slope of marginal revenue curves in a world of segmented markets [6]. Wald also exhibited this possibility for the Cournot case with marginal revenue of upward slope. Then Bonanno explored the Robinson type case with the smoothly shifted demand curves and fixed cost curves in a catastrophe theory [7].

In classical economics, economists mainly focused on the theory of static or equilibrium economy rather than non-equilibrium economy or dynamics. The equilibrium study is in general simpler and may serve as a useful preparation for the more difficult non-equilibrium and dynamics. In late nineteenth century, the neoclassical economists provided fruitful mathematical analysis of the equilibrium in an idealized market economy. With the progress of economy, some prominent economists started to realize the importance of nonequilibrium economics and the truly dynamic economy. Marx argued that there would be cycles in employment and income shares in a highly simplified economy composed of capitalists and workers. The famous Goodwin's model of cyclical growth was inspired from Marx and provided a cyclical vision of economy [8,9]. The defect of the equilibrium Say's Law/Walras's Law is that the role of credit is ignored [2]. The depiction of the equilibrium economic theory is the "general gluts" (as an excess of supply in relation to demand) and depressions are impossible because of the spontaneous equilibrium. Schumpeter, Marx and Minsky pointed out that the depressions and "general gluts" are possible once the fallacy is removed. Schumpeter focused upon the role of entrepreneurs in capitalism and presented the vision of cycles driven by entrepreneurs search for profit [8,10,11]. Fisher's debt-deflation theory claimed the viewpoint of cycles and potential collapse caused by private debt [12]. Keynes also suggested that the economy cannot spontaneously attain equilibrium due to uncertainty and fragility of expectations [13]. In summary, those kinds of the economic cycle and crisis phenomena cannot be perfectly comprehended in a statics and equilibrium system. More recently, economists such as Steve Keen also suggested the idea and concept of nonequilibrium economics [14,15].

As discussed, in the conventional economy, the supply and demand have often been described as having a monotonic trend. Higher price is accompanied with higher production quantity for supply. On the other hand, lower price is accompanied with higher demand in quantity for demand. This is often under the assumption of the complete competition market and close equilibrium economy. However, in reality, incomplete market competition, open non-equilibrium economy rather than closed economy, inflation and under-employment, and overproduction etc. are present and can alter the simple monotonic trend to be nonlinear and non-monotonic. As a result, the multiple stable states can emerge. In some cases, the limit cycle oscillation can appear. The underlying trend can no longer be determined by the simple shift of the single equilibrium as in the conventional supply–demand dynamical analysis in economy. The challenges are then to formulate a quantitative theory for non-equilibrium economy to address the issues of how to globally and quantitatively describe the multiple stable states and limit cycle oscillations in a non-equilibrium economy, how to identify the driving forces for non-equilibrium economy, and how to describe the dynamical process (characterized by paths and speed) from one state to another for the economy in the more general and realistic non-equilibrium cases other than the idealized simplified equilibrium cases.

In this work, we developed a landscape and flux theory to meet the above challenges for describing the general dynamics of non-equilibrium economy. We first define the economic state as determined by the collection of the specific values of the underlying state variables such as price, production quantity and many others. Then the state can be described as one point in this multidimensional space of variables. The dynamics of economy can be seen as the evolution from one state to another in this multidimensional space. Since there are in principle many such states in the multi-dimensional state space, not every state is equally probable. We quantify the states of economy by identifying the multi-stable states as the basins of attractions on the underlying probabilistic landscape with higher probabilities. The market in a specific economic state can fluctuate around specific price and production. Once the fluctuations of price and production are large enough to overcome the barrier of underlying landscape, the market can enter into another state of economy from the current state and achieve a new steady state. It is worthwhile emphasizing that our approach of quantifying non-equilibrium economic dynamics with states and state transitions in between is in contrast to the conventional quantification of economic dynamics as equilibrium shift.

We uncovered the driving forces of economy, one is from the underlying landscape gradient derived from the steady state probability distributions and the other is from the curl probability flux which measures the degree of detailed balance breaking or the exchange with outside for open non-equilibrium economy. The dynamics of economy thus resembles an electron moving in an electric (landscape gradient) and magnetic field (curl flux). Notice the conventional equilibrium economic dynamics does not have this landscape perspective. Furthermore, the conventional equilibrium dynamics in complex systems only has the landscape gradient as the sole driving force. It does not have the curl flux component. However, the economy is an open and non-equilibrium system. That is why both landscape gradient and curl flux are playing the key roles in determining the general non-equilibrium economic dynamics.

In the conventional equilibrium economy, the supply and demand often have only one equilibrium point and the dynamics is described as the shift of the equilibrium. By considering nonlinear supply–demand dynamics in open non-equilibrium economy, we found that both bi-stable states and limit cycle oscillations can emerge. In this model, the