Complexity change in system's structure as a result of space symmetry rupture: an example from transport system

F. Ruzzenenti (*), R. Basosi# (*) (**)
(*)Center for Complex Systems Investigation, University of Siena, Italy,
(**)Department of Chemistry, University of Siena, Italy.

Keywords: space symmetry rupture, structural complexity, complexity leap

Abstract

Constructal theory predicts structures, both in nature and in human artefacts, tend to optimize flow access. The systems' architecture develops from a principle of maximization of one function under local constrains. The domain of this optimization is a continuous space. We would like here to advance an example in which the system structure is reshaped in a more energy intensive fashion as to maximize the components' interactions due to a symmetry rupture in the space. Flows throughout the system are thereby incremented in a *discontinuous* way by a complexity leap. Nevertheless, the complexity leap is a step of the developmental pattern that displays the same trend in constructal theory's models: flow maximization. In this paper, we analyze how the productive system evolved its structure, between 1970s and 1990s, to maximize interactions among its parts and thus further develop the transport sub-system. A two-stage shift has been considered: the fordian and the post-fordian productive structure. The second structure, given the same amount of parts, has been shown to increase the degree of freedom (path length and path diversity) of the system. The underlying evolutionary pattern is then analyzed. This evolutionary pattern relies on the hypothesis that thermodynamic evolutionary systems are characterized by an ever growing influx of energy driven into the system by self-catalytic processes that must find their way through the constraints of the system. The system initially disposes of the energy by expanding, in extent and in the number of components, up to saturation due to inner or outer constraints. The two counteractive forces, constraints and growing energy flux, expose the systems to new gradients. Every new gradient upon the system represents a symmetry rupture in the components' space. By exploring a new gradient, the system imposes further restrictions on its components and increases its overall degree of freedom.

Nomenclature

DAT	Daily average traffic across a testing spot on a road, sampled over a year
GDP	Gross domestic product
Intra-industry Index	Two-way international monetary flows of goods within standard industrial classification
Tkm	Tons per kilometre of goods delivered

1. Introduction

In this paper we will use an example drawn from transport system and productive structure in order to illustrate how a symmetry rupture in system's space may underlie a structural complexity leap. Such a leap is the outcome of two counteractive forces: an increasing energy influx on the one hand and hindering boundary conditions on the other. Boundary conditions become compelling when they oppose to system's expansion.

In the first section it will be introduced the case study here adopted as example of the aforementioned thermodynamic evolutionary pattern. It will be shown that: the energy influx was

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[#] Corresponding author: basosi@unisi

driven by higher energy efficiency of transport means; that the productive structure has dramatically changed thereafter (it will be particularly addressed the question of time-consequence of events); that such a structural changed produced a growth in distance but also in *frequency* of shipments. It will be shown that the new structure (post-fordian) has to be regarded more *traffic intensive* by means of an indicator, implemented in the context of Italy: the D.A.T., daily average traffic. This indicator shows that freight transport increases as a result of an interactions' intensification among structural parts of the productive system, on an international level.

In the second section the question of the complexity leap will be addressed. It will be shown to what extent the new productive structure should be regarded as a more complex one in respect to the previous one. As a matter of fact, it will be illustrated how the degree of freedom of the new structure have augmented throughout.

In the third section the complexity leap will be set on a broader theoretical framework, addressing the evolutionary pattern that drives such a change. It will be shown how saturation (hindering boundary conditions) of quantitative growth (in extent and number of components) creates the condition for a symmetry rupture in system's physical space. This rupture sets a new gradient –a spatial gradient, formerly *invisible* to system's components, into the system's physical space. This new gradient will pave the way for the onset of a new structure, as system's components will rearrange their organization according to it. This process will be illustrated by means of example drawn by physical and human-made systems.

2. Case study

In this case study we analyze how the productive structure changed in Europe between the 1970's and the 1990's in a fashion that interactions among productive plants were maximized. The shift from a *fordian* (uni-located productive chain) to a *post-fordian* (pluri-located productive chain) came after a dramatic energy efficiency improvement in the field of transport sector (road transport, mostly), that was reflexily caused by the oil crisis [1]. This major shift, which featured *globalization*, is commonly named *outsourcing* and, as it heavily relied on logistics, it boosted transport service demand.

During the two decades, the energy efficiency of trucks displayed a remarkable evolution. We have here considered a series of driving tests, consistent in terms of the road, driving conditions and speed. Tests concerned 111 different European trucks, ranging from 1978 to 1998. *Fuel economy* (litres of fuel per every 100 km) improved by about 30% [1] [2].

In Europe, during the same time range, the tkm on the road network increased significantly by 130% [3]. It is noteworthy that in the tkm grew more on the side of production means than on the side of final products [4]. In other words, factors markets were more influential than goods markets in driving the demand for transport service [5].

The more suitable indicator to detect the process of *outsourcing* is the Intra-industry Index [6] [7]. This indicator measures the value of international trades *within* the same sector or industry and it is thus determined by the exchanges of raw materials, productive means and semi-products in addition to services integral to the production process. According to this indicator, in 1970 in Europe trades of productive means were 56% of international commerce, and 71% in 1990 [7]. These figures grew of 10% between 1970-1980, of 20% between 1980-1990 and of 12% in the following decade. In the aftermath of the first oil crisis (1973), the road freight transport system underwent a drastic, worldwide renovation in an attempt to reduce oil-derived fuel consumption. In the EU, turbocharged engines and aerodynamics elements were adopted in the heavy duty sector and weight limits were abruptly raised in order to reduce fuel economy of long distance vehicles [2] [7]. Therefore, the energy efficiency change in the road freight transport sector should be regarded as a *cause* of structural change in economy (*globalization, outsourcing* and *post-fordian*).

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[1] Between this time and *adjusted fuel economy* (fuel economy divided by the engine power, in order to account for the power increase) reveals that efficiency actually grew by about 50%

2.2 Traffic density: a clue of the intensity of travels (interactions)

The shift from a uni-located (fordian) productive chain to a pluri-located (postfordian) one, together with the integration of markets, placed an increasing burden on the road transport system. The fuel use in the freight transport sector grew not only because the mean distance of travels augmented, but also because the *frequency* changed. In other words, the outsourcing system of production is strictly connected with a more *intensive* transport system. According to this view, the growth in tkm is not only due to market integration, but also to the outsourcing process itself.

If transportation augmented not just because of the average distanced, but also because the frequency of movements, it is arguable that local network, and not just long-distance network, would have consequently been affected. That is to say, traffic density growth has to be detected on a local scale.

In order to get a realistic picture of local traffic density, it is important to reduce the scope of the analysis. As it is necessary for traffic density data to be consistent over time and space a single country has been considered, as study case. Data from the traffic census in Italy between 1972 and 1989 [8] have been analyzed. The traffic census in Italy roughly occurred every five years and was set on 398 tracking points scattered throughout extra-urban roads all over the Italian road network. These sites have remained relatively unchanged over the years. Data were collected on eight days (six working days) and four nights during all seasons. Vehicles were arranged into eight categories, four of which were goods vehicles. DAT (Daily Average Traffic) expresses a weighted average[2]of the vehicles on the road every day during the year. A sample of 44 tracking points scattered all over Italy that were significant based on location (on roads connecting either productive sites or big urban conglomerates) have been selected. According to these data, while total vehicles grew by 25% in 25 years, goods vehicles (over three tons) grew by 132% (much more than the 54% growth in industrial production during the same interval of time). Semi-trailers trucks, used mainly for international duties, grew by 172% (Table 1).

Table 1 DAT: daily average traffic. Italy, 1972-1989

	Goods Vehicles up to 3 tons	Single Unit Trucks over 3 tons	Trailers Trucks	Semi-Trailers Trucks	Total Vehicles
1972	673	624	335	112	12.297
1979	669	602	296	171	11.451
1985	881	639	261	246	14.199
1989	840	566	239	301	15.340
	24,75%	-9,25%	-28,80%	169,56%	24,75%

Source: elaboration on ANAS traffic census, 1973-1990

Statistics above matches the rate of growth of tkm (180%) that occurred in Italy during the same time period, further confirming the impression that shipments increased much more for the density than for the distance of travels.

It is important to consider that freight transportation grew not just in distance travelled, but also in frequency of shipments. The density of connections can be regarded as a footprint of structural complexity of the productive system.

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[2] The average is weighted over the course of one year in order to represent the daily traffic of an average day and thus, to balance seasonal peaks and tufts.

3. Complexity leap: structural analysis

The complexity change occurred in the productive structure needs to be discussed. The main feature of the shift from a fordian to a post-fordian system concerns the location of the productive chain. Formerly, the productive chain was set thoroughly in one site, to which raw materials were delivered and from which products were shipped. From the 1970's onward, big companies began disassembling the production chain and placing it in several, scattered structures, often in foreign countries. As a matter of fact, the productive chain changed shape thereafter. We will use graph theory in an attempt to illustrate how the productive structure evolved in complexity. Graph theory helps to establish whether a determined shape can be considered more complex than another. It is therefore suitable to compare the complexity of abstract structures, but cannot be considered a tool for measuring complexity.

Graphs in Figure 1 display some sketches of the productive structure. They focus on the inflow of materials, the supply and productive chain, and assume that the outflow, the product distribution chain, is not affected by the structural change being analyzed. The graph A shows a "fordian" factory in which the materials of semi-products flow from suppliers to the centre where the productive chain is concentrated (the star-like graph).

The graph B shows a "post-fordian" factory in which the suppliers become part of the "spread" productive linear chain (the square-like graph). The dashed line indicates that we can consider it to be both an open loop (no main plants) and a closed loop if the final assemblage occurs in the plant where the process started.

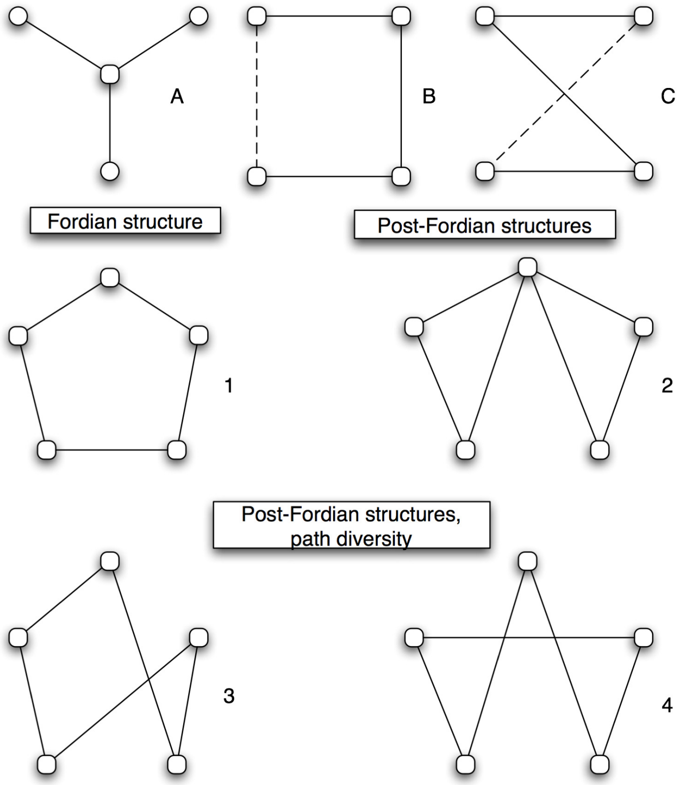

Figure 1 Graph theory, productive chain analysis

Graph B is more complex in shape than graph A even though it has the same number of points (and lines, in the open loop case) because:

I. The minimum degree (minimum number of incident lines to each point) of graph points is higher in the closed loop case.
II. Connectivity (minimum number of points whose removal results in a disconnected or trivial graph) is higher in the closed loop case.

III. The path length is four (three if open loop) times that of graph A.
IV. The number of possible path-cycles across the points is two times that of graph A. In other words, there are, at least, two non isomorphic graphs (graphs B and C) that connect the points in a chain, while there is only one in a star-like structure like graph A[3].
V. The number of non isomorphic graphs increases if we consider a chain of more than four points (graphs 1 to 4), while the number of star-like graphs remains the same. This means that there is just one structure that connects many points to a center while there are many different structures that make a chain (open or closed) out of the same number of points.

Hence the post-fordian structure presents a higher degree of freedom and thus relates to a more complex system.

A system with a higher degree of freedom is a more complex system in the sense that, as for any physical system, it has increased multiplicity or number of different available states. In other words, a more complex system has more ways to dispose of particles, in this case, goods or raw materials, and therefore to dissipate energy.

4. Complexity leap as a result of space symmetry rupture

According to the hypothesis here advocated, complexity increases when the system can rearrange its components in order to increase the number and the path length or the speed of interactions, within the same boundaries. The complexity leap herein described can be further traced in various systems. An example in cells is represented by the internal skeleton of microtubules that increase the speed of molecules across the cell by means of diffusion. In ecosystems, there are food chains and predator-prey dynamics. This hypothesis expresses view of complexity based on the concept of geometry. According to Lotka *geometry* is a peculiar feature of thermodynamic of living systems and thus, of a sort completely different from those normally addressed by physics. Whereas the latter mainly deals with "structureless systems", of the like of chemical coefficients, the former must approach "geometrical features" [9]. Complex systems display a spatial gradient which is sometimes many orders of magnitude larger than gradients on a molecular scale [10].

4.1 The complexity leap: new states with higher degree of freedom, achieved pursuing new spatial gradients

Recently, Fath gave a full survey of *ecological goal functions* (ecological orientors or extremal principles) [4] and showed that, although seemingly incoherent, they are congruous when considering the three fundamental properties: maximize input and direct flows; maximize retention time; maximize cycling [11]. According to Fath, these goals or orientors are mutually consistent and interdependent of fulfillment. All the ten evaluated goal functions, in light of these orientors, depict the coherent behavior of ecological systems. Fath also emphasizes that the network structure is the arch-key that makes this possible [11].

According to us, the network structure development that eventually results in complexity growth at any system level, is the outcome of forces (energy influx driven by autocatalytic processes) in the context of hindering boundary conditions. It is the simple growth (in extent and in number of

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[3] In other words, there is just one way to go from the periphery to the center, regardless of the number of nodes considered, while there are many ways to connect the same number of points in the path. Furthermore, the number of different ways increases with the number of points. This does not mean that, in a scattered productive chain, factories (points), are connected randomly, but instead means that there are multiple ways for a chain to develop its pattern and just one for a centralized system.

[4] Maximum power (Lotka), maximum storage (Jorgensen; Mejer), maximum empower and emergy (Odum), maximum ascendency (Ulanowicz), maximum dissipation (Schneider; Kay), maximum cycling (Morowitz), maximum residence time (Cheslak; Lamarra), minimum species' dissipation (Onsager; Prigogine), and minimum empower to exergy ratio (Bastianoni; Marchettini).

components) the normal behavior in the absence of such boundary conditions. That is to say, without hindering boundary conditions, the system expands its structure, qualitatively unaltered (spatial growth). The system develops in a primary and spatial manner initially, then, when saturation is reached, in a secondary and geometrical (structural) one. It is such geometrical development that enables the system to increase its degree of freedom and to host more energy (or energy density rate) within the same constraints. When this complexity change emerges, the incoming structure, albeit already available to system components, becomes now more probable. The boundary conditions ultimately determine the likelihood of the new structure.

It is also true for simple physical systems that changing a system's boundary conditions alters its degree of freedom. For example, if the pressure of a gas increases, its degree of freedom decreases and it consequently becomes a liquid. At the same time, when a liquid changes its motion regime, as in Benárd cells, from a pure, random dissipative system to a global dissipative one, which displays features several magnitudes larger than molecules, a superstructure arises that was previously available yet very unlikely. Gravity and viscosity constraints make such a structure, beyond a certain level of energy (heat) input, possible. The random motion of molecules reflects one gradient, the temperature, which is not spatial (geometrical), while the superstructure is exposed to the spatial gradient. That is to say, while the first gradient is defined by one variable, the latter is described by three variables and probabilities consequently change. Dissipation onto one variable is therefore more probable than onto three variables, unless boundary conditions render the former impossible. In Benárd cells, such conditions are exemplified in Van der Waals forces, the low heat capacity of water, and restrained vessel thickness [10] [12].

The connectivity recasts the same trade off in a network system's conceptual framework. A network system grows in complication as long as a new component is connected on the same hierarchical level and it grows in complexity when a new component is introduced on a higher hierarchy [13]. The emergence of a new hierarchy entails coherent behavior for lower level components to the same extent as molecules in Benárd cells and most importantly, the onset of a new spatial gradient[5] for the higher component which must now recognize system boundaries.[6] On a molecular scale, cells in the body behave like a network. From the standpoint of the organism, however, they act as a whole unit. It is indeed true that "free" cells in substrates are mainly exposed to chemical gradients (temperature, pressure and gravitational gradients as well), while "embedded" cells in tissues that form organs are described by spatial, three dimensional, gradients.

The case study here considered -the dynamical interplay of energy efficiency in the transport sector and productive structure, displays the same evolutionary pattern of structural change to a system of greater degrees of freedom. This pattern also seems to exhibit the same trend towards higher system gradients. The system, in order to change its degree of freedom, explores new gradients previously inaccessible to its components. The extent to which the shift from a fordian to a post-fordian productive structure increases the degree of freedom of the productive system was formerly discussed. The increased hierarchy and the emergence of a network-shaped, wide productive chain in place of a star-shaped one, highlight the incremented degree of freedom of the system. Such higher degrees of freedom were obtained by the system's search for new and more favorable economic conditions for production, such as different labor, stocking, and supplying costs. For example, after globalization, firms could explore labor costs according to various national legislations and average incomes. The same occurred for financial and fiscal conditions or the proximity to productive districts. All the factors became variables for the firms to optimize by

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[5] It is noteworthy that, from a cybernetic point of view, degree of freedom (number of independent variables) and gradient (vector of derivatives of the dependent variable on the independent variables) are both correlated to the introduction of new variables in the system where the amount of components are held constant. This notion indeed constitutes an obstacle to the attempt of modeling evolution.

[6] Cell division in developmental stages follows essentially a spatial gradient, like those regulated by homeotic genes.

allocating, fiscally or economically, part of the production (or capital) chain to several countries. What was predominately about negotiation with policy makers, labor unions or banks, became a matter of logistic and transport costs. Firms could thereby reduce production costs by selecting where to set plantations or rely on supplies. It is in this sense that globalization produced the *rise of new spatial gradients in the productive system.*

4.2 Spatial symmetry rupture

The statement about the system searching for new gradients may appear teleological. Teleology looms in this paradigm in the form of a sentient agent, the system, looking for gradients. It is indeed a misrepresentation of the actual process, which occurs probably because of changing boundary conditions, and is due to semantic more than logic. As a matter of fact, the rise of new gradients concerns the space wherein the system develops itself. A new gradient springs out of a spatial symmetry rupture[7]. The symmetry rupture is due to two counteractive forces: system's components are mutually exposed to some hindering forces (viscosity and gravity, in the case of Benàrd Cells), formerly negligible or absent, and an increasing energy influx (the heat gradient). Symmetry in space can thus be re-established when such forces cease or are surmounted (temperature rises over a certain threshold in the case of Benàrd Cells).

It is an external force that on the one hand reduces the degree of freedom of single particles and on the other, by introducing a new gradient, collectively enables the system to augment its degree of freedom by achieving new forms of organization (of several order of magnitudes bigger). Degree of freedom of particles and system are thus inversely related, as determined by the "symmetry rupture".

It is noteworthy that laws of mechanics are based on the homogeneity and isotropy of space. The random motion of gas molecules are thus described, microscopically, by kinetics because gravitational force is negligible and symmetry in space is maintained. In the case of liquids gravitation exerts its influence and spatial symmetry is broken (Figure 2). The degree of freedom "lost" form single molecules in the phase transition is "regained" collectively in the system structure. The symmetry rupture, caused by the introduction of further constrains to the system (viscosity and gravity) imposes a new gradient to the system, which is "exploited" by particles to generate a new structure.

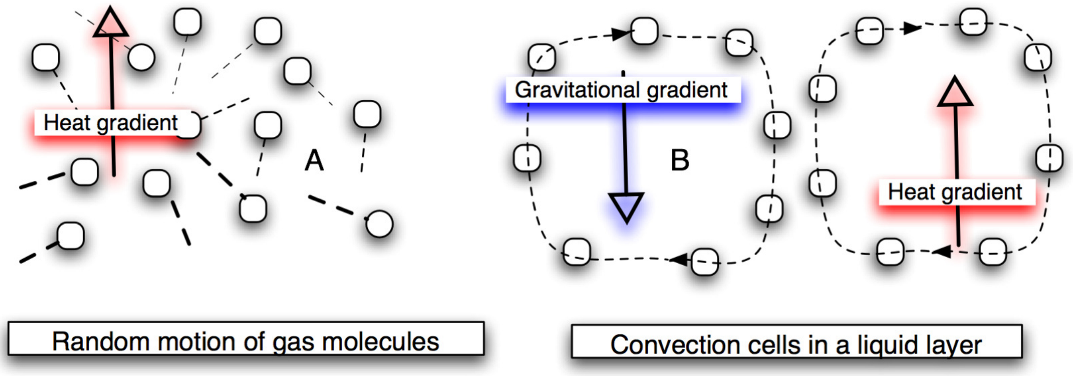

Figure 2 Space symmetry rupture in a fluid system

We believe economy (and macroscopic complex systems in general) exhibits a similar evolutionary pattern: a space symmetry rupture emerges from compelling boundary conditions and increasing energy inflow. In the case of the productive structure's evolution it can be shown that space was isotropic in the former state (fordian) and non isotropic in the latter (post-fordian): a spatial

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[7] These spatial symmetries are represented by transformations that describe those situations where a property of the system does not change with a continuous change in location. For example, the temperature in a room may be independent of where the thermometer is located in the room.

symmetry breaking occurred (Figure 3). What made this spatial gradient rise was a reduction firms' degree of freedom in production setting, coupled with a energy efficiency leap. More energy was thus available to the system amid a condition of hindering forces applied to its boundaries. Two counteractive forces are beneath a symmetry rupture in the physical space of the system. In this case the symmetry rupture put a space gradient upon the system and force it to organize its variables according with. *Globalization* and *outsourcing* set production plants in a new, oriented space that was formerly homogeneous.

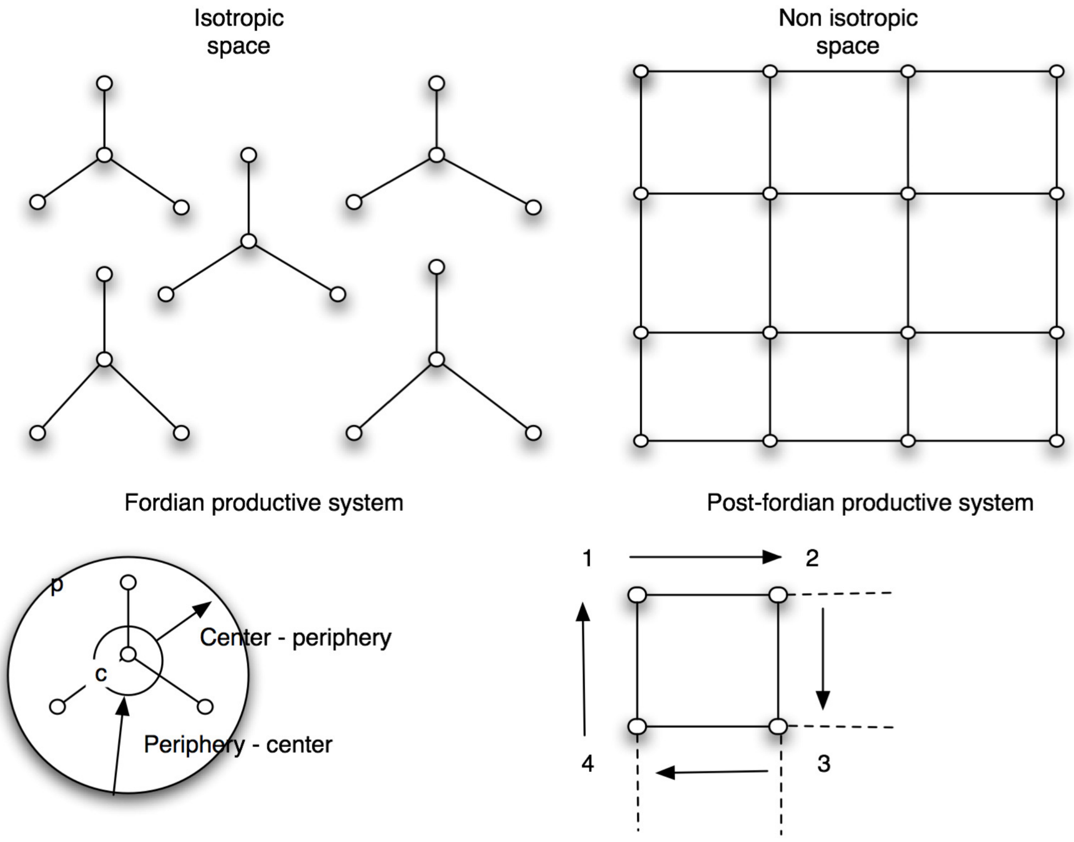

Figure 3 Space symmetry rupture in the productive system

5. Conclusions

In this paper it has been made an attempt to propose how space symmetry rupture can be regarded as a condition, among others, for complexity growth. It is possible that complexity, whenever it grows in a discontinuous fashion exhibits a transition of the sort described here. A transition whose main change concerns, besides the system, its physical space. We thus believe that a symmetry rupture in system's space plays an important role in understanding complexity leap. However, in the analysis presented here, the process of structural change has not formally been addressed, as it is in Costructal Law. The way forces interact functionally in order to generate new shapes, was not the included in our analysis. We have instead been more concerned with the conditions, related to the system's space, that generate such a change. We hope that this will help to shed light on the fact that forthcoming paradigms addressing the question of shape generation in the field of complex systems should consider the relevance of the problem of *discontinuous changes* (complexity leap).

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