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ENDOGENOUS KNOWLEDGE EXTERNALITIES:
AN AGENT BASED SIMULATION MODEL WHERE SCHUMPETER MEETS MARSHALL

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ENDOGENOUS KNOWLEDGE EXTERNALITIES: AN AGENT BASED SIMULATION MODEL WHERE SCHUMPETER MEETS MARSHALL [1]

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ABSTRACT. The paper elaborates an agent based simulation model (ABSM) to explore the endogenous long-term dynamics of technological and structural change determined by Schumpeterian reactions to unexpected changes in the system that are made possible by the actual availability of Marshallian knowledge externalities that are at the heart of economic growth. From this viewpoint ABSM, as a form of artificial cliometrics, provides the opportunity to explore the role of endogenous knowledge externalities for the long run dynamics of the system. The results of the simulations confirm that endogenous knowledge externalities have powerful effects on the equilibrium conditions of the system dynamics at the micro, the meso and the macro levels. At the micro-level the reaction of firms caught in out-of-equilibrium conditions yields successful effects with the introduction of productivity enhancing innovations only when and where positive pecuniary knowledge externalities are actually available. At the meso-level the out-of-equilibrium dynamics of endogenous knowledge externalities affect the structural characteristics of the system. Endogenous centrifugal and centripetal forces re-shape continually the structure of the system. At the macro system level the out-of-equilibrium process leads, to step-wise increase of productivity for the system as a whole, while individual commons are exposed to non-liner patterns of output growth characterized by significant oscillations that take the typical form of long waves, familiar to the Schumpeterian analysis of business cycles.

Keywords: Complex System Dynamics, Innovation, Emergent Property, Endogenous knowledge externalities.

1. Introduction

The notion of externalities has been introduced by Alfred Marshall (1890, 1920) to account for the dynamics of increasing returns without undermining the assumption of constant returns to scale at the firm level.

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Output can increase more than proportionately than inputs when occurrences that are external to each firm but internal to the system affect positively the result of the production process. The notion of externalities has found widespread application in economics at large and has acquired, more specifically, a central role in the economics of innovation and technological knowledge. Knowledge externalities play a crucial role in our understanding of the generation and use of technological knowledge.

Technological knowledge in fact is nowadays viewed as an interactive and collective activity consisting in the recombination of internal and external knowledge made possible by the intentional interaction and participation of a variety of learning agents, embedded into geographic and professional knowledge commons. Interaction is requested in order to acquire and implement external knowledge, an essential input into for the generation of new knowledge.

The characteristics of the landscape into which knowledge interactions take place have a central role in assessing the actual viability of knowledge generation strategies. The viability of knowledge generation depends upon knowledge externalities. Knowledge externalities in turn depend upon the characteristics of the landscape. These characteristics however are neither static nor exogenous. They keep changing through time as a consequence of the mobility of agents searching for new opportunities to generate technological knowledge. The changes in the rugs of the landscape can deploy both positive and negative externalities affecting the actual capability of firms to innovate. Such changes in the capability of firms to generate new technological knowledge in turn affect the mobility of firms and hence ultimately the rugs of the space. Rugged landscapes and hence knowledge externalities are not given elements, but the endogenous and path dependent product of a collective process (Sorenson Rivkin and Fleming 2006).

The generation and dissemination of technological knowledge in fact take place in organized contexts characterized by qualified interactions among heterogeneous and creative agents that are able to act intentionally to innovate when their performances are out of equilibrium. The outcome of their interactions is determined by the structured contexts into which they are embedded. At the same time, however their interactions do affect the structure of the system, the amount of pecuniary knowledge externalities that are available within the knowledge commons and hence ultimately the aggregate productivity.

Changes in productivity levels affect the price level of the system, and the performances of firms, engender new out-of-equilibrium conditions that in turn stir new attempts to react by means of the generation of additional amounts of knowledge, supported by research activities and strategic mobility across knowledge commons, and the introduction of technological innovations (Schumpeter 1947).

An open-end system of feedback is put in place with continual interactions between individual action and endogenous knowledge externalities that stem from the structure of the system. In this approach both the decision to generate technological knowledge and introduce technological innovations taking advantage of knowledge interactions and the organized structures into which they take place are endogenous, as they are determined internally by the dynamics of the system. The individual and intentional action of creative agents is central in the dynamics of the system, yet no individual agent can claim responsibility or even long-term sight on the eventual results of his or her action, because of its effects on the organization of the system (Miller Page 2007).

To elaborate this approach, the paper builds upon a synthetic account of the role of externalities in the economics of technological knowledge, implements the notion of endogenous knowledge externalities, showing the dynamic endogeneity of the emergence and decline of knowledge externalities at the system levels and explores its implications on the rates of increase of the productivity of the system.

The paper is structured as it follows. Section 2 reviews the changing appreciation of knowledge externalities and elaborates the theoretical framework to grasp the endogeneity of knowledge externalities. Section 3 presents the agent-based model of the innovation system. Section 4 exhibits the results of the simulation focusing upon the alternative hypothesis about the institutional and architectural features of the innovation system. The conclusions summarize the main results and elaborate the policy implications of the analysis.

2. Knowledge Externalities

2.1. Knowledge as a public good

The matching between the Marshallian notion of externalities and the economics of knowledge emerges from the early investigations of technological knowledge as an economic good. Technological knowledge is an economic good, characterized by non-appropriability, non-excludability, non-rivalry in use, non-exhaustibility and non-divisibility. These peculiar characteristics of technological knowledge, as an economic good are at the origin of substantial market failures, as inventors cannot retain the full control of the stream of benefits engendered by the generation of new technological knowledge and the introduction of new technologies (Nelson 1959).

The identification of knowledge non-appropriability, non-exaustibility and non-divisibility not only as a source of market failure, but also as an opportunity, lead to the fertile crossroad between externalities and economic of knowledge with the discovery of technological spillovers. Technological knowledge spilling from one firm can benefit other firms. Adam Jaffe (1986) and Zvi Griliches (1979, 1992) paved the way to using the notion of externalities in assessing the external effects of the R&D activities of each firm upon the generation of knowledge by the other firms within the system. They identify the notion of proximity in knowledge and regional space and quantify the contribution of external knowledge that spills from the research efforts of other firms and public research laboratories and can be used in the production of new knowledge by other parties engaged in similar research activities. The empirical investigations pioneered by David Audretsch and Maryann Feldman (Audretsch Feldman 1996; Feldman 1999) provide substantial evidence about the advantages exerted by technological externalities on the innovation output and the productivity growth of firms co-localized in the same geographical space. The notion of spillovers, available freely in the atmosphere, very much like manna, has provided the analytical ground upon which the new growth theory has been elaborated and implemented (Romer 1986 and 1990).

In these studies spillovers are treated as an unpaid factor that enhances the efficiency and the output of passive recipients. Technological knowledge generated by a given firm is an unpaid factor that enters freely, at no cost, and with no intentionality, the production function of other firms. Imitators can take advantage from technological knowledge produced by innovators without paying any costs. The notion of pure (technological) externalities elaborated by Meade (1952) is clearly the basic reference.

2.2 The generation of knowledge as a recombinatory process

A major step in a more articulated appreciation of knowledge externalities has been made with the discovery of the key role, as a necessary input – as opposed to an occasional, additive production factor-of external knowledge in the generation of new technological knowledge. Technological knowledge is not only the output of a generation process, or the result of an activity, but also an input, not only for the production of other goods, but also for the production of new technological knowledge. Actually it is strictly necessary for the recombinant generation of new technological knowledge and learning agents need to search and access it intentionally (David 1994; Weitzman 1996 and 1998; Fleming 2001).

In order to generate new knowledge, in fact, firms need to combine internal sources of knowledge such as intramuros research and development activities and learning processes with the systematic use of external knowledge that is now considered as an indispensable input for the general production of new knowledge. No firm, in fact, can innovate in isolation. External knowledge can be substituted to internal sources of knowledge only to a limited extent: full-fledged substitutability between internal and external knowledge cannot apply. External and internal knowledge, both in their tacit and codified form, are complementary inputs where none is disposable. Technological knowledge is seen more and more as collective activity rather than a (quasi) public good (Fleming Sorenson 2001).

Consequently, external knowledge has a crucial role. In the generation of knowledge, firms act as 'integrators' of internal skills and competence with external sources of knowledge. Knowledge external to the firm, at each point in time, is a necessary and relevant complement to knowledge internal to the firm, if new knowledge is to be generated. The conditions governing the access to external knowledge are a key factor in assessing the chances of new knowledge being generated. Firms that have no access to external knowledge and cannot take advantage of essential complementary knowledge inputs can generate very little, if any, new knowledge at all, even if internal learning combined with research and development activities, provides major contributions. Also the opposite is true. Firms that do not perform any knowledge generating activity but have access to rich knowledge commons can generate no new knowledge (Chesbrough 2003; Chesbrough Vanhaverbeke West 2006; Lokshin Belderbos Carree 2008).

External knowledge is only potentially useful: systematic efforts have to be made in order to exploit such possibilities. To do this, firms rely on knowledge exploration strategies to identify the sources of knowledge and to assess whether and to what extent they can rely upon external or internal knowledge to produce new knowledge. Only when a firm is able to fully coordinate all the relevant learning and research activities conducted within its boundaries with the relevant sources of external knowledge, both tacit and codified, can new knowledge be successfully generated. Technological spillovers are no longer viewed as windfall benefits that benefit passive recipients. In order to take advantage from external technological knowledge firms need to implement intentional actions, conduct dedicated search activities and bear dedicated costs (Beaudry Breschi 2003; Bresnahan Gambardella Saxenian 2001; Bresnahan Gambardella 2005).

2.3 The role of knowledge interactions in the generation and use of technological knowledge

The appreciation of the key role of knowledge tacit-ness and sticky-ness marks a third step. Technological knowledge is inherently sticky and has a strong tacit component. It is difficult and costly to spell out all the ingredients, procedures, applications and implications of knowledge. Only after systematic efforts of codification, technological knowledge can be transferred. Knowledge is embedded in organizations, protocols and procedures. Hence it can be shared and acquired only by means of direct interactions that entail specific costs. External knowledge can no longer be regarded as spilling freely in the atmosphere (Arrow 1969; Mansfield Schwartz Wagner 1981; Cohen Levinthal 1989 and 1990).

The identification of and the access to external knowledge are expensive not only in terms of actual purchasing costs, when and if markets for knowledge exist, but also and mainly in terms of knowledge governance costs. Knowledge interactions are necessary to access external knowledge because of its tacit content and because of the difficulty to assessing the actual quality of the knowledge when the vendor bears the risks of opportunistic behavior and dangerous disclosure (Lundvall 1988).

The acquisition of external knowledge requires qualified interactions with other agents: dedicated effort is necessary to create the institutional context in which external knowledge can be acquired. The capability of agents to access external technological knowledge depends on the fabric of institutional relations and shared codes of understanding which help to reduce information asymmetries, limiting the scope for opportunistic behavior and building a context into which reciprocity, built-up trust and generative relationships can be implemented. The receptivity of each firm to knowledge generated elsewhere is not obvious: its levels vary across firms and intentional activities are necessary to implement it (Cohen and Levinthal 1989 and 1990, Antonelli 1996).

The creation and implementation of absorption and receptive capabilities engender knowledge governance costs that include all knowledge transaction, communication and interaction costs associated with the exploration activities such as search, screening, processing, contracting, and interacting with competitors, suppliers and customers (Griffith, Redding and Van Reenen 2003; Guiso and Schivardi 2007).

A related line of enquiry has shown that the effects of the agglomeration and proximity of knowledge generating activities are not always and universally positive. Negative effects and increasing costs can characterize agglomeration within geographic and technological clusters as a result of reduced appropriability of proprietary knowledge (Jaffe 1986). Congestion problems and negative effects on technological learning and innovation can also easily arise due to excess proximity and agglomeration and consequently lock-in, inertia, higher communication costs, and redundant interaction structures between actors. As it is well known the number of communication channels that are necessary to interact increase exponentially with the number of agents. The wages of scientists and talented people are likely to increase with the increase in the density of knowledge generating activities (Stephan 2011).

The identification of the tacit-ness and sticky-ness of technological knowledge and the appreciation of the central role of interactions among knowledge possessors and knowledge users for actual knowledge transfer to take place has the important implications. Knowledge externalities are now viewed as intrinsically local, as opposed to global. Knowledge interactions take place in a context characterized by communication channels and knowledge interfaces that stress the role of proximity. They cannot take place in vacuum (Rui and Swann 1998).

The new role of external knowledge now viewed as a necessary and costly input in the recombinant generation of new technological knowledge, the appreciation of the local context into which external knowledge can be actually used and knowledge governance costs leads to elaborate a new analytical framework based upon the notion of pecuniary externalities put forward by Scitovsky (1954). Pecuniary externalities consist of indirect interdependences among actors. These interdependencies take place by means of intentional transactions and interactions that exert their effects on the cost equation. Pecuniary externalities take place as long as the costs of inputs are lower than equilibrium levels due to specific external conditions. As a consequence, pecuniary externalities apply instead of pure (technological) externalities in assessing the role of external knowledge (Antonelli 1996).

The application of the notion of pecuniary knowledge externalities, well distinct from that of pure (technological) externalities enables to account for both positive and negative effects associated with knowledge externalities. While the former consist of the advantages associated with the opportunities each firm has to learn and 'absorb' technological knowledge generated elsewhere (i.e., other firms, universities, public R&D labs), the latter are the costs of the exploration, interaction, transaction, absorption, recombination of knowledge that cannot be fully appropriated by "inventors". They vary according to the characteristics of the system (Antonelli 2011).

Pecuniary externalities is a fertile tool of analysis that, makes it possible to appreciate what determines and affects the different levels of costs of external knowledge as an essential input. External knowledge does not freely spill over into ambient. External knowledge can be accessed at a specific and well-identifiable knowledge governance costs that vary according to the different characteristics of the local context.

This approach enables to qualify from an economic viewpoint the actual bottom line complementarity of learning agents within and across knowledge commons. The knowledge possessed by two agents can be highly complementary but knowledge governance costs can be so high that the interaction is not possible because it is impeded by negative knowledge externalities. KN models moreover do not quantify the actual contribution of external knowledge to the generation of new knowledge. From this viewpoint our approach provides better understanding of the economics of knowledge generation than the KN model where the levels of knowledge complementarity have not an appropriate economic characterization in terms of costs and benefits (Levinthal 1997, Sorenson Rivkin Fleming 2006).

In some specific locations heavy governance costs add to the purchasing costs of external knowledge. In others, knowledge governance costs are very low: the access to the knowledge commons is easy and the total costs of external knowledge, including purchasing and governance costs are much lower than their marginal productivity. Such circumstances however do not hold everywhere and all the time, but only in highly idiosyncratic conditions. Such circumstances, moreover, are endogenous to the local system as they depend both on the endowment of firms with high levels of competence, and the varying levels of density of each system and the related levels of external knowledge (Bischi Dawid Kopel 2003; Zhang 2003).

Both the positive and negative pecuniary knowledge externalities depend upon the density of innovative agents co-localized in the same region. It is clear that the larger is the density of innovative agents and the larger is the opportunity to access their knowledge spillovers, but is also clear that the larger is the density of innovative agents and the larger are the costs of using them. The density of learning agents that try and perform knowledge interactions within a knowledge common has a direct and strong bearing upon the actual levels of knowledge governance costs and hence on the levels of net pecuniary knowledge externalities.

Not only too little, but also too much proximity can be detrimental to the accumulation and creation of technological knowledge and the innovative capabilities of the firms. The mobility in regional space of agents seeking to access external knowledge available within fertile knowledge commons has direct effects on the actual levels of knowledge governance costs. Here the notion of endogenous knowledge externalities becomes clear.

This analysis leads to identify an optimal size of knowledge commons. Too little a density of innovation activities reduces the accessibility of external knowledge. Too large a density enhances congestion and reduces appropriability. Firms can benefit from actual increasing returns stemming from the indivisibility, replicability and non-exhaustibility of knowledge only when the size of innovation networks is comprised between the two extremes. The empirical evidence confirms that knowledge externalities do trigger increasing returns that are external to each firm, only within a well-defined interval, beyond which decreasing returns to scale take place. Knowledge externalities are a property of the system into which firms are embedded. As such they are endogenous to the system and likely to exhibit specific properties related to the changing characteristics of the system itself. The quality of knowledge governance mechanisms in place plays a key role in assessing the actual size of the net positive effects of knowledge externalities.

In sum, the characteristics of the system, into which knowledge flows, matter in terms of knowledge governance costs including transaction, interaction and communication costs. Because of the intrinsic non-exhaustibility and non-divisibility of knowledge, the costs of external knowledge, after taking into account its governance costs, may be lower than the long-run equilibrium cost as defined by the matching between marginal costs and marginal product. This important occurrence is strongly influenced by the levels of knowledge governance costs that in turn reflect the characteristics of landscape. When the costs of external knowledge are below equilibrium levels firms can actually innovate and their reaction becomes creative. The introduction of innovations is clearly an emergent property of the system; as such it takes place only in specific and positive geographic, institutional and sectoral contexts. The structural characteristics that make possible the provision of positive knowledge externalities, and hence the introduction of technological innovations, however, are local, as opposed to global, far from being static or exogenous: they are determined by strong endogenous and localized dynamics (Krugman 1994).

2.4 The complexity of endogenous knowledge externalities

The recent efforts to apply the basic tools of complex system analysis to social sciences and to implement an actual economics of complexity are particularly helpful for the purposes of this paper. In this frame, in fact, the generation of technological knowledge can be effectively analyzed as an endogenous collective process, that is both the key causal factor and the determinant of the dynamics of a system. Technological knowledge and innovation is the emergent property of organized contexts characterized by qualified interactions among heterogeneous and creative agents that are able to act intentionally to innovate when their performances are out of equilibrium. The individual and intentional action of creative agents is central in the dynamics of the system, yet its results are determined by the structure of the system and the endogenous dynamics of knowledge externalities. No individual agent can claim responsibility or even long-term sight on the eventual results of his or her action. The interdependence between individual action and structural change engenders the complexity of the system (Lane 2002 and 2009, Page 2011).

The analysis of the dynamics of pecuniary knowledge externalities makes it possible to grasping their endogeneity. The actual levels of pecuniary knowledge externalities are in fact external to each firm but internal and contextual, localized into the system into which firms are embedded and change according to their actions.

In the generation and use of technological knowledge, both positive and negative externalities apply and exert their effects. Positive externalities, are endogenous as they depend upon the amount of knowledge possessed by each other agent as determined by upon the innovative behaviors of the agents and in the relevant past, because of the role of learning. Yet, at each point in time the amount of positive knowledge externalities can increase if and when agents achieve higher levels of knowledge. Negative externalities, as it is clear, are also endogenous as they depend on the levels of knowledge governance costs determined by the density of agents –accumulated through time- in the system and the ensuing amount of knowledge interactions that the members of each knowledge common need to implement. At each point in time the levels of negative knowledge externalities may change as a consequence of the mobility of agents.

Negative externalities stem not only from the higher levels of knowledge governance costs associated with higher levels of density but also from the general effects of mobility and hence innovation on the price at the system level[2]. Mobility of agents across knowledge commons and intentional efforts to increase the command of technological knowledge has a second and critical effect on the system. The successful entry in a rich knowledge common increases the opportunities to absorb external technological knowledge. This leads to the enhanced generation of technological knowledge and the faster introduction of productivity enhancing innovations with the consequent decline in product markets of the transient equilibrium price. The reduction in the price levels engenders new out-of-equilibrium conditions that push new firms to try and innovate, inducing additional mobility across knowledge commons and increased efforts to generate technological knowledge with new loops of instability and structural change. Pecuniary externalities easily accommodate the price effects as soon as we consider the levels of output in value.

The appreciation of negative externalities makes it possible to understand the interplay between the positive and negative effects of localization in both regional and knowledge space. Some threshold effects can be identified, according to which co-location and agglomeration exert a net positive effect on the absorption and exploitation of knowledge spillovers but only until a certain extent. Beyond a given threshold, 'too much' agglomeration and 'too' dense networks can spoil the positive effect of knowledge externalities.

Pecuniary knowledge externalities are endogenous to the system as they reflect the changing distribution of co-localized members within knowledge commons and inherently path dependent because they stem from the elements of past dependence well articulated by the stock of firms that belong to each knowledge common at each point in time, with

[2] Pecuniary externalities stemming from the reduction in product prices are clearly negative for the firms in the system that experience a fall in performances, but positive for their consumers.

the pervasive role of contingent factors such local interactions, feedback and strategic mobility of firms. The mobility of firms affects the actual levels of net positive externalities available in each location. The entry of new firms is likely to increase the overall levels of knowledge governance costs and the same time it may increase the opportunities for knowledge sharing. The exit of firms, on the opposite, helps reducing the overall levels of knowledge governance costs but reduces the opportunities for knowledge sharing. The mobility of firms is fully endogenous as it stems from the search for better opportunities to generate new technological knowledge that is activated by out-of-equilibrium conditions. At the same time the mobility of firms affects the actual opportunities for the generation of new technological knowledge, by changing the structural conditions of the system.

The rugged landscape into which firms are localized is not an exogenous characterization of the system but it is intrinsically endogenous as it is determined by the mobility of firms[3]. The dynamics of the system is continuously fed by the interplay between out-of-equilibrium conditions, reactions of firms, enhanced learning processes, search for external knowledge, mobility in knowledge space, structural changes, new balance of knowledge externalities, generation of new technological knowledge, introduction of productivity enhancing technological innovations, reduction of prices and new out-of-equilibrium conditions. Endogenous knowledge externalities are at the heart of the system.

At each point in time any solution can be found, but such solution has not the standard characteristics of stability and replicability. Each equilibrium point is erratic. Small shocks, engendered by the mobility of firms seeking to absorb higher levels of external knowledge, have major effects at both the aggregate and disaggregate levels, and may push the system far away from any given values. No forces will act to push the system back towards the levels experienced in the previous phase. The actual performances of individual agents and of the system at large depend upon the distribution within the system of agents across knowledge commons, their density and their endowments in terms of knowledge levels. Each of these key elements is interdependent with the others and stem from the dynamics of ever changing collective dynamics.

Path dependence, because of the role of learning and interdependence deploys here its powerful effects. The stock of available knowledge and

[3] NK models assume on the opposite an exogenous definition of the density of components of the landscape and of their K complementarity (Levinthal 1997).

the systems of knowledge communication in place, at each point in time, catch the effects of past dependence. Small events, however, can push the system to change the direction and the rates of the dynamics with effective consequences that change the trajectories set by past dependence (David 2007).

The actions of learning agents, in fact, do affect the structure of the system: knowledge interactions together with internal earning efforts affect the distribution of knowledge possessed by each agent and yet accessible by means of knowledge interactions; mobility across knowledge commons affects the density of agents and hence the amount of knowledge governance costs. The actual levels of pecuniary knowledge externalities that are available within the knowledge commons and hence ultimately the amount of knowledge that the system at large can generate and the aggregate outcomes of the dynamics in terms of productivity levels, are at the same time endogenous and unpredictable, exposed to the changing interplay between individual action and structural change. In this approach neither interactions nor the organized structures into which they take place are exogenous, as they are determined internally by the dynamics of the system (Arthur 2009; Arthur et al. 1997; Lane et al. 2009; Antonelli 2011).

3. The simulation model[4]

3.1. The architecture of the model

The working of the system of interactions and transactions that qualify the simple but articulated economic system outlined in the previous section can be explored by means of a agent based simulation model (ABSM) in order to investigate the schumpeterian dynamics of the innovation process in a Marshallian system (Pyka and Fagiolo, 2005). ABSM provides with the opportunity to explore the full range of implications of a multilevel structure of interactions and transactions as framed in the previous section and to take into account the variety of outcomes of the decisions taken by each heterogeneous agent (Dawid, 2006; Terna 2009).

The ABSM implemented in this section operationalizes, through the interactions among a large number of objects representing the agents of our system, the working of a typical complex process characterized by the key role of Marshallian externalities and augmented by the

[4] This chapter elaborates and updates the general description of the simulation model provided in Antonelli and Ferraris (2011).

Schumpeterian assumption that firms are credited with the capability to try and innovate according to the levels of their performances and the context into which they are localized (Schumpeter 1947).

The model assumes that the rationality of firms is bounded and adopt satisfactory criteria of conduct based upon procedural rationality. Firms are endowed with the capability to learn and to react. Their reaction is determined by out-of-equilibrium conditions when profitability levels are far away from the average. The reaction will be actually creative and lead to the introduction of productivity enhancing innovations, instead of adaptive adjustments of quantities to prices, when and if positive knowledge externalities are available (Antonelli 2008)

In the ABSM demand and supply meet in the market place; production is decided ex ante; firms try and sell their output in the product market, where customers spend their revenue. The matching between demand and supply sets temporary prices that define the performances of firms. Firms are learning agents, according to the levels of their performances and the availability of external knowledge firms can fund dedicated research activities to try and innovate.

In the simulation, heterogeneous firms produce homogeneous products sold into a single market. In the product markets the households expend the revenues stemming from wages (including research fees) and the net profits of shareholders. In the input markets the derived demand of the firms meets the supply of labour provided by workers, including researchers. For the sake of simplicity, no financial institutions have been activated, nor can payments be postponed. Shareholders supply the whole capital of the firms and all the commercial transactions are immediately cleared.

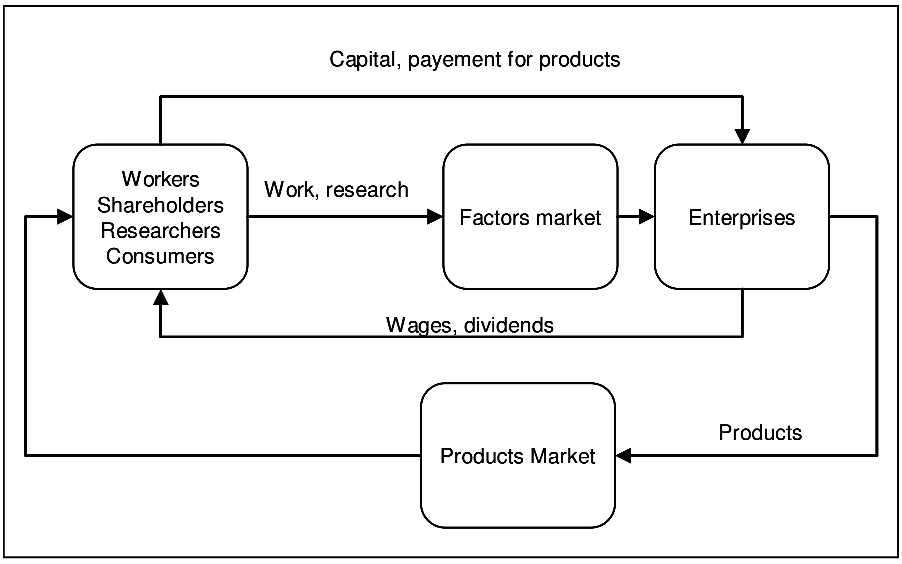

Figure 1: Flows into the simulated economy

Market clearing mechanisms based exclusively upon prices maintain a perfect equilibrium between demand and supply. Such equilibrium is ensured for both the product and the factor markets: the quantities determine the correct price for which the whole production can be sold. No friction neither waiting times are simulated, factors are assumed to be immediately available.

The production function is very simple, in order to avoid matters related to different kinds of production processes, inputs availability, warehouses cycles and so on: outputs depend exclusively from the amount of employed work and its productivity. Both labour and productivity vary among firms: labour depends on the entrepreneur's decision about the growth of the production. Productivity is a function of the technological level the firm achieved through innovation.

The whole output is sold on the single product market, where the revenue equals the sum of wages, dividends and research expenses and the price depends on the liquidity. According to the temporary price levels, profits are computed as difference between income and costs, no taxes are paid, neither part of the profit can be retained into the enterprise. Shareholders either will receive the profits or reintegrate the losses. Firms can support their losses only to a threshold beyond which they leave the market and will be replaced by new entries, after a parametrical number of production cycles.

Firms are heterogeneous both with respect to their levels of productivity and hence ultimately profitability and with respect to their location. The economic system is represented as a collection of regions, or commons, across which firms are tossed at the start of the simulation process. Firms are characterized as learning agents. Firms learn internally by doing and externally by interacting. Internal learning processes are intrinsic to the firm and take place spontaneously through time. External learning takes place at two levels. First, internal learning rates take place at a rate that is influenced by the local conditions of their common. The accumulation of competence via learning processes of each firm is larger, the larger is the average productivity of all the other competitors localized in the common. Second, we assume that localization in a common provides also the opportunity to absorb technological knowledge from co-localized firms with higher levels of productivity. External learning entails specific knowledge governance costs that are necessary to carry out the necessary activities of knowledge networking and communication with all the other members of the common. Knowledge governance costs depend upon the number of firms within each common and each firm carries on such costs independently of the need and opportunity for external learning. Knowledge governance costs increase more than proportionately with the density of agents that belong to the same common: mobility across commons has a direct bearing upon the costs levels (See the next section for more details).

The whole system is represented as nested collection of agents: agents are grouped in commons that are simple collection of agents, as well as the whole system consists in a collection of commons (a collection of collections of agents). The figure 2 shows the logical layers into the ABSM model focusing the two different macro level to be distinguished: the macro system level and the macro common level.

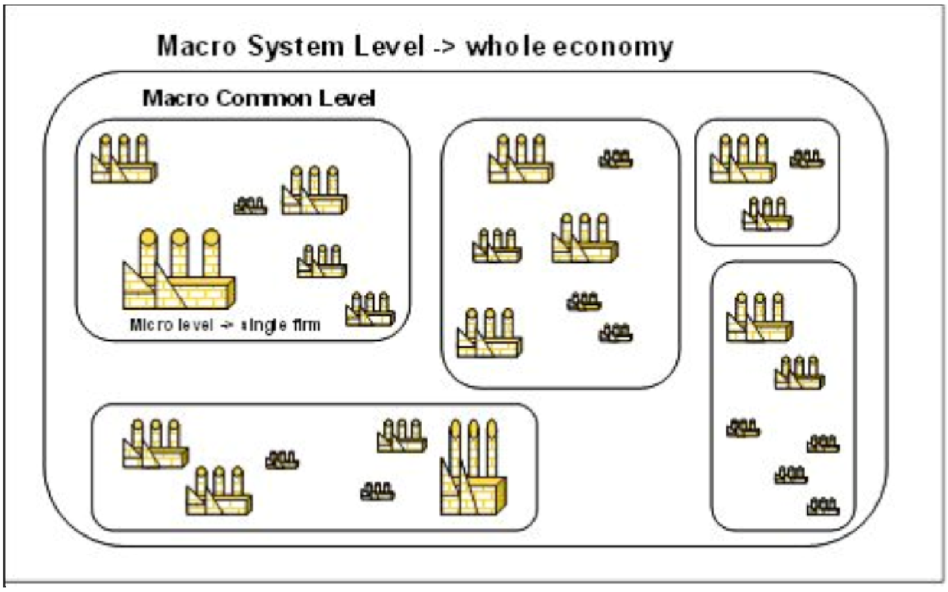

Figure 2: Logical layers of the simulated economy

Trough the simulation process the localization of the agents in the different commons is the result of their past activities and yet they can change at each point in time. The results obtained during a production and consumption cycle influence the strategies the agents will take during the next cycle. Hence the dynamics of the model is typically characterized by path dependence: the dynamics in fact is non-ergodic because history matters and irreversibility limits and qualifies the alternative options at each point in time. At each point in time, however, the effects of the initial conditions may be balanced by occasional events that may alter the 'path' i.e. the direction and the pace of the dynamics (David 2007).

Firms perform basic search functions and acquire information about the levels of profitability of their neighbour firms that belong to their same common. Because of bounded rationality the firms into the model are not able to observe all the economic system, but the average levels of profitability of all the other firms. Individual transparency is clearly local: the ray within which firms can observe the conduct of other firms is limited to the common.

The farther is profitability from the local average and the deeper the out-of-equilibrium conditions. Firms can innovate if the results are under the average level, to improve their performances, as well as when the results are above the average level, to take advantage of abundant liquidity and reduced opportunity costs for risky undertakings. Innovation is viewed as the possible result of intentional decision-making that takes place in out-of-equilibrium conditions. The farther away is the firm from equilibrium and the stronger the likelihood for innovation to take place. Hence we assume a U-relationship between levels of profitability and innovative activity, as measured by the rates of increase of total factor productivity[5].

Summarizing, the firm increases its motivation to innovate each time its performance is found to be far enough from the local average. Such a motivation become stronger and stronger if the enterprise's relative position remains outside a band for several and consecutive production cycles: after a parametrically set number of consecutive cycles the enterprise performs an innovation trial.

Out-of-equilibrium conditions push firms to try and react by means of the generation of technological innovations that increase their productivity. The attempts to generate new technological knowledge and hence to innovate are based upon internal research and learning efforts and upon the access to external knowledge available both within and across commons. The search and access to external knowledge can be both local and global. When the neighbourhood into which each firm is embedded does not provide sufficient opportunities to generate additional

[5] The empirical evidence of Antonelli and Scellato (2011) supports the hypothesis and helps assessing the parameters of the simulation model.

technological knowledge firms can move in knowledge space across commons and get closer to firms with high levels of technological knowledge. The absorption of external knowledge requires dedicated resources and specific costs, as much as the mobility across commons to get closer to firms with higher levels of productivity.

Following a growing empirical evidence upon the intrinsic characteristics of agents' dynamics we characterize the search activities that are at the base of the innovation process with the typical traits of the *Levy flights* to our learning firms and we suppose that firms alternate expended phases of local search within their own common with long jumps that bring them to other commons (Barabasi, 2010).

Hence we assume that the actual generation of additional technological knowledge takes place when the learning firm is able to master successfully a sequence of three steps consisting in: i) the valorization of internal competence based upon learning processes, ii) the local absorption -within the common- of external knowledge, iii) the entry in a new common possibly characterized by net pecuniary knowledge externalities (See the next section for more details).

The successful generation of new technological knowledge enables the introduction of productivity enhancing innovations. Their introduction, in turn, reduces the overall price level in the product markets and hence created new out-of-equilibrium conditions. The loop between micro and macro dynamics is closed and engenders continual growth and change, provided the changes in the structure of the system do not engender the provision of positive net knowledge externalities. The interaction between individual action and systemic change includes the structural changes determined by the mobility of firms across knowledge commons and its effects on knowledge governance costs. Endogenous knowledge externalities are the engine of the system dynamics (Anderson Arrow Pines 1988; Rosser 1999 and 2004).

3.2 A detailed presentation of the simulation of the innovation process

Since the focus of the paper consists in the identification of the changing role of endogenous knowledge externalities in the innovation process we shall explore in this paragraph with special care the details of the ABSM of the innovation process and stress analytically the role of the external factors that shape the recombinant generation of technological knowledge.

Firms are characterized as learning agents. Learning is both internal to the firm and external:

i) Internal learning is a routine that includes typical processes of learning by doing and learning by using. Internal learning enables the accumulation of tacit knowledge and potential competence that requires a specific action to be eventually mobilized and transformed in actual technological knowledge. The rates of accumulation of each firm are influenced by external learning processes.

ii) External learning is also a routine and consists in a monitoring activity that enables firms to assess the profitability levels of the other firms co-localized within the common and assess the levels of their productivity. External learning relies upon the interaction with the other firms that belong to the same common. Because of bounded rationality, firms can observe only the other ones that belong to their own common. External learning provides the relevant information about the actual availability of external knowledge that can be tapped when and if the firm tries to upgrade its productivity levels. External learning consists of two processes: i) faster learning rates that are influenced by the average productivity of the common, ii) the possibility to absorb technological knowledge from co-localized firms with higher productivity levels. External learning entails specific knowledge governance costs that increase more than proportionately with the density of agents that belong to the same common (March 1991).

Agents follow a satisfycing approach both in the decision to try and innovate and in the identification of the satisfactory amount of innovation. At each point in time learning firms confront their own profitability with that of the firms co-localized within the common. If their profitability is either below or above the local average firms react so as to try and innovate to increase their productivity. Their reaction may be adaptive or creative according to the actual availability of knowledge at costs that below the marginal product: innovation efforts are expensive because innovation is not free. Firms are short-sighted and expend in one unit of time all innovation costs, including absorption costs, even if the productivity gains obtained by means of absorption last more than one (1) unit of time. Innovation efforts may fail when the costs of innovation exceed the productivity gains. In this case the reaction of agents will be adaptive. Innovation efforts may succeed and hence make the reaction creative when knowledge is actually available at costs that are below its marginal product.

The innovation process consists of a sequence of three sequential steps. At first firms try and mobilize their own internal slack competence. The firms that have not sufficient potential competence based upon past learning processes try and absorb the external technological knowledge spilling from their within-common neighbours and, if knowledge absorption is not possible, they can move randomly to another location in a new common. Let us consider them in turn:

a) firms can mobilize their internal slack competence accumulated by means of learning processes. The firms of the model are endowed with the ability to learn better ways to perform their production cycles. Each time a production cycle is done, firms acquire and cumulate some technological potential. Such a potential can be transformed in actual innovation only by means of intentional and dedicated research activities. The competence can be transformed in real innovation at a cost. Because the internal slack competence is seldom sufficient to support the recombinant generation of new technological knowledge and hence the actual introduction of a productivity enhancing innovation, firms that have explored the common into which they are localized, try to access and absorb the knowledge of firms of their neighbours.

b) local absorption enables to take advantage of the technology introduced by other firms. Firms can take advantage of the information acquired by means of external learning processes and are able to identify the other co-localized firms that enjoy higher levels of profitability. Absorption however can take place only with dedicated activities: because of absorbing costs however it is not free. The effective access to external technological knowledge requires substantial resources in exploration, identification, decodification and integration into the internal knowledge base.

The absorption of knowledge from other firms with higher levels of productivity is not free and un-limited. First of all absorption of external knowledge requires dedicated activities that command specific resources that identify absorption costs. Their levels depend upon the productivity gaps between the recipient and possessor. Second, absorption is limited by intellectual property rights (IPR). A major constraint to the possibility to take advantage and absorb others' technologies is represented by (IPR). In order to model a credible IPR regime we allow enterprises to patent their technology and hence to retain exclusive exploitation rights for a certain number of cycles. By observing other firms each firm knows the latest technological level they apply that is not covered by a patent licence. The key parameter "patent expiration" is used to experiment different scenarios, its value determines the number of production cycles each innovation remains hidden to the competitors. It is plausible to expect that the longer is the patent period, value of the patent expiration parameter, the higher will be the research effort: unless enterprises were given the exclusive possibility to exploit the research results, no private firms would be interested in investing money, because their discovery would be immediately available for competitors. In the model, even with patent expiration equal to zero, the new technology is exploited exclusively by the innovating enterprise for almost one cycle (Reichman 2000). Thirdly, actual and effective absorption take place stochastically. Occasionally the actual absorption of higher levels of productivity of other firms may fail.

When knowledge absorption gives poor or null results, firms move into another location in order to meet better technological conditions.

c) mobility across commons. The third way to improving productivity levels consists in moving around the physical space in order to reach more interesting commons. When the mobilization of competence and within-common knowledge absorption are not viable solutions, firms can try and move randomly to another location in the hope to find superior commons where the stochastic possibility to absorb technological knowledge from firms with high productivity levels is higher. Since firms do not have access to individual information about all the other firms in the system, but those located within their own common, the Levy flight is actually blind. The move can lead to superior commons as well as to inferior ones. Specifically firms decide to move only if the profitability of their common is below the system average. If the average profitability of their common is above the system average, the chances to find a superior common would be too low.

Here we see how the structure of the system influences in several ways the innovation chances of the enterprises: the localization in an advanced common is beneficial because: i) learning is faster, and ii) perspective recipients have higher possibilities to observe and absorb technological knowledge that high-productivity firms cannot fully appropriate. At the same time however the localization in a dense common engenders high costs both for learning and for knowledge governance.

3.3 Endogenous knowledge externalities and the dynamics of the system

Let us now summarize the key points of the ABSM to stress the relevance of endogenous knowledge externalities for the dynamics of the system.

The appreciation of the endogeneity of knowledge externalities enables to grasp the characters of endogenous growth shaped by the intrinsic path dependent dynamics of the system both at the structural and the macroeconomic levels.

At the start of the simulation, heterogeneous firms, localized in different commons, are endowed with different levels of productivity, randomly tossed for each into the lowest quarter of the possible values, following a uniform probability distribution. Firms start the production process with their own productivity levels, try and sell their goods on the product market and experience different levels of profitability. They compare their own profitability with the average of the common to which they belong. When their profitability is either below or above the local average of their-own neighbourhood, firms try and change their knowledge base so as to introduce technological innovations. The innovation efforts are successful if their costs are below their gains in terms of productivity in one unit of time. The costs of knowledge play a central role in assessing the viability of innovation efforts.

Innovation efforts consist of a sequence that starts first with the valorisation of their internal competence based upon internal learning processes that are influenced by the local average levels of productivity. If the internal competence is not sufficient to actually introduce a new technology, so as to increase their productivity, firms make the second step that builds upon the information gathered by means of knowledge governance activities and consists in the attempt to try and absorb the knowledge of other firms, co-localized within the same common, with higher profitability levels. If such firms are not available locally firms make the third step: they try and move out of the original common. Because of bounded rationality, however, firms are not able to assess whether the levels of knowledge governance costs of the new common are lower than the advantages stemming from external knowledge. The jump is blind. As a consequence of a negative outcome, firms keep moving across the system from one common to another.

The ensuing mobility of firms has important consequences on the structural landscape of the system and on the endogenous generation of knowledge externalities. The location in a knowledge common in fact is expensive as it entails knowledge governance costs that consist in the resources that are necessary to searching, screening, assessing the levels of knowledge of the neighbours and to activate communication channels and networking activities with them. Consequently knowledge governance costs are determined by the density of firms in a knowledge common. Hence the mobility of firms across commons affects the knowledge governance costs of all the other members of the common. Exit of a firm reduces their knowledge governance costs. Entry of new firms increases them. The levels of net pecuniary knowledge externalities available in a knowledge common are strictly endogenous to the local system with important dynamic effects.

The distribution in space of agents, tossed randomly at the beginning of the process, becomes fully endogenous as agents move in regional space, across knowledge commons, searching for the access to external knowledge spilling in the proximity of high-productivity firms. At the same time, because pecuniary knowledge externalities are endogenous, the actual levels of net pecuniary knowledge externalities that are available at each point in time within each knowledge common change over time as a consequence of the mobility of learning agents and the consequences in terms of knowledge governance costs for all the members of the knowledge commons.

Hence the dynamics of the regional distribution of agents exhibits the typical traits of path dependence. The process is non-ergodic but not past-dependent: small variations may exert important effects in terms of emergence of strong commons or, on the opposite, determine their decline and force firms to exit with their progressive dissemination in space. At the system level excess entry in 'fertile' knowledge commons can stop the generation of new technological knowledge and affect the rate of increase of productivity: net pecuniary knowledge externalities are reduced to zero by excess knowledge governance costs. This is most likely to take place exactly where high-productivity firms are located as their higher levels of technological knowledge are likely to benefit firms, that are willing to innovate and were located originally in other commons[6].

The introduction of productivity enhancing innovations affects the position of the supply curve and modifies the conditions of the product markets: price fall as well as the profitability of all incumbents. Firms re-assess their own profitability levels with respect to the local average and the process is likely to keep going, provided the changes in the structural conditions of the system stemming from the mobility of firms in the space have not engendered the provision of knowledge externalities. The mobility of firms is the prime internal factor of the endogenous dynamics

[6] The empirical evidence of Antonelli Patrucco Quatraro (2011) supports the hypothesis and helps assessing the parameters of the simulation model.

of the landscape and hence of the endogenous determination of the levels of knowledge externalities that shapes the viability of the innovation process at the firm level (Antonelli, 2011).

This loop affects the system on four counts. Specifically we expect to see:

i) at the firm level, the actual levels of endogenous knowledge externalities may inhibit or foster the successful introduction of innovations;
ii) at the structural level, the dynamics exerted by the interplay between centrifugal and centripetal forces change the structure of the system and the attractiveness of the different commons. When knowledge governance and absorption costs exceed the benefits stemming from external knowledge, centrifugal forces are at work: the density of commons declines with the exit of firms. Centripetal forces are instead at work when on the opposite the benefits of external knowledge are greater than the sum of knowledge governance and absorption costs: the size and density of the common increases. The structure of the system is characterized by changing heterogeneous 'stains' with commons where the introduction of productivity enhancing innovations takes place and commons where no innovation is possible. The distribution of 'stains' will keep changing over time;
iii) at the common level the dynamics of output and productivity will be characterized by typical Schumpeterian waves as the changing interplay between centrifugal and centripetal forces engenders different phases that affect the overall, aggregate rates of productivity and output growth that exhibit both growth and decline;
iv) at the macro-system level the dynamics of the system is likely to exhibit step-wise process of growth of output and productivity. The wave-like change at the common level in the aggregate engenders a positive outcome with phases of fast growth shaped by the upsides determined by the prevalence of the centripetal forces and phases of slow growth where the downsides that take place because of centrifugal forces exert a stronger impact.

4. Results

The strength of the ABM consists in the possibility to assess in a coherent and structured frame the systemic consequences of alternative structural configurations of the properties of the system. Simulation techniques allow to exploring the outcomes of different hypotheses concerning key issues of the model within a structured and consistent frame that takes into account the full set of direct and indirect effects of the interactions of agents (Pyka Werker 2009).

The results of the simulation confirm that the model is consistent and able to mimic the working of a complex system where rent-seeking agents react to the changing conditions of the product and factor markets. Hence the results confirm that the model is able to portray the working of a complex system based upon a large number of heterogeneous agents on both the demand and the supply side that are price taker in product markets. Markets clear with temporary equilibrium price. The replication of the temporary equilibrium price in the long term confirms that the model is appropriate to explore the general features of the system when the reaction of firms is adaptive and consists in price to quantity adjustments. In the extreme case where firms cannot innovate for the lack of internal competence to be mobilized and external knowledge to be absorbed, the system mimics effectively the working of static general equilibrium in conditions of allocative and productive efficiency but with no dynamic efficiency. The markets sort out the least performing firms and drive the prices to the minimum production costs. This result is important because it confirms that static general equilibrium is the simple and elementary form of complexity that takes place when agents cannot innovate. As soon as agents try and succeed in their reaction to changing market conditions with the introduction of innovations, the equilibrium conditions become dynamic and all the key features, such as the prices, the quantities, the efficiency and the structure, of the system keep changing (Antonelli 2011).

The results of a very early set of simulations confirm the crucial role of endogenous knowledge externalities: the simulation based upon the hypotheses of no externalities have produced poorer results in terms of productivity growth than simulation where externalities were at work. The dynamics of the simulated system exhibit a wave-shaped trend due to the continuous research for more profitable commons the firms perform. These results have been achieved by using a plausible but non fully calibrated parameters configuration so they need to be confirmed by a deeper investigation able to reinforce and confirm these early analysis.

Accordingly to the simulation results, the existence of different areas in a economic system where productivity grows with different pace and profits follow different distributions in time could emerge as an endogenous effect due to the decision taken by each firms about relocation. In this process commons are continuously stretched and contracted: new firms arrive as well as old ones could move to other commons, hardly ever the balance between incoming and leaving agents is able to maintain the commons population stable, so their size is varying each simulation step.

Depending on the commons capability to retain agents (the *Levi-flight* is blinded so agents move randomly to new commons, but they stay into the common if their profit are close to the average profit at the macro common level or the common profitability is greater than the average profitability of the whole economy) a single common could operate as an attractor dramatically expanding its size. The more a common grows the higher become the knowledge governance costs for its firms. When costs overcome the benefits due to knowledge externalities, the profits of the firms start to fall inducing them to try and find more profitable commons by relocating.

Simulations demonstrate that the distribution of firms –and consequently the actual levels of net knowledge externalities- is the product of an endogenous process: starting from a uniform distribution of firms in ten different commons the continuous relocation the agents perform produce a sequence of growth and decay of the commons accordingly to the level of net pecuniary knowledge externalities their aggregation are able to engender.

The high technological and productivity level achieved into the more developed commons tends to spread around when firms belonging into those commons start moving away to others less developed. The average productivity level shows few differences among commons because firms in less developed ones rapidly spill the higher knowledge brought by the new entries coming from more developed commons when the centrifugal forces prevail. The decay of a big common becomes a way to share the effect of knowledge externalities among other commons and provide high opportunities for less developed firms to make a dramatic jump toward higher productivity.

An initial set of experiments with the same parameters configurations but different random distributions has been run to test the robustness of the ABSM: the behaviour of the system showed itself to be independent from such variations, so its results can be assumed to be systematic and reliable.

The second group of simulations, whose results are presented here, concentrated on the following specific topics:

1. Existence and effectiveness of the externalities, mainly based upon the comparison of results obtained in scenarios where externalities had different intensity. Each scenario has been named with Greek letters: i) Alpha represents the benchmark scenario with the full deployment of both knowledge externalities: internal learning enhanced by the average productivity of the common and opportunities to absorb external knowledge, and knowledge governance costs, ii) Beta excludes both knowledge governance costs and enhanced internal learning but allows the absorption of external knowledge, iii) Gamma excludes knowledge governance costs but allows internal learning with fixed rate for accumulation of experience, fully independent from the average productivity of the common, iv) Iota excludes knowledge governance costs and allows only internal learning with fixed rate for accumulation of experience.
2. Dynamics of the benchmark scenario, Alpha, where accumulation of experience proceeds at a faster pace in more developed commons but knowledge governance costs grows more than proportionally than population.
3. Dynamics with different IPR regimes (Phi scenario).
4. Dynamics with different number of commons (Theta scenario).

All the simulations of the second group have been computed using very close parameter's set up - few values were changed among the different scenarios - the same number of agents, duration, and number of commons and, finally, the same random distribution, in order to increase the full comparability of the results. More in detail each scenario simulation has been run for two thousand production cycles, involving one thousand agents. Scenarios alpha, beta, gamma and iota used ten commons, whereas in the scenario Theta agents were grouped in four commons only because this scenario was set to study the influence of a different dispersion of agents. Except the Phi scenario where the IPR protection lasts for two production cycles only, the new technologies are preserved from spillover for five production cycles in all the other scenarios.

At the onset of the simulation the levels of productivity were tossed at random for each firms between 0 and 0.25 following a uniform random distribution, firms were endowed an initial cumulated knowledge randomly tossed between zero and 0.1 that is the minimum knowledge amount suitable to be transformed in an increase of productivity.

Information among agents has been allowed only inside each common, where agents have been made able to potentially observe each time all the others one belonging into the same common even when their number became quite large. Agents did not have any information about commons they do not belong to, but they knew the average profitability of the whole economy (macro system level), and, indeed, they knew about the commons they did belong to (macro common level).

When an agent's cumulated losses exceeded a parametrically fixed threshold, that agent went out of business; after few cycles (another parameter) its place was taken by another agent endowed with technology equal to the average level of the common.

Existence and effectiveness of the externalities.

The investigation has been based upon the comparison among results obtained by running simulations of four scenario (Alpha, Beta, Gamma and Iota), obtained by varying the values of the two key parameters: "knowledge governance costs" and "external opportunities" that influence the actual effects of the localization in a common upon the accumulation of competence and the capability to absorb external knowledge.

More in detail, knowledge governance costs are computed for each firm according to the density of the commons to which they belong. Density exerts a non-linear effect so that knowledge governance costs for each firm increase at a rate that is faster the larger the number of firms co-localized within the same common. Whereas in the first (Alpha scenario) this parameter was set to 1.05, in the other ones (Beta, Gamma and Iota scenarios) the whole cost was set to zero. The "external opportunity" parameter measures the effects of the productivity external to each agent that he will pile on its internal knowledge at each production cycle. According to our model firms localized in a high productivity common accumulate more competence than firms localized in a low productivity one. This parameter received three different values: i) in the Alpha and Theta scenario it was set to 0.001 times the average productivity of the agents that belongs into the common, ii) in the Beta one the amount of experience earned each production cycle was set to zero, i. e. no experience was cumulated at all, iii) in the Gamma and Iota scenario, mainly devoted to test the effectiveness of different setups for this parameter, the firms earned 0.001 of experience for whatever productivity level the commons reached. The following table 1 resume the set ups for the experiments.

Table 1: Alpha versus others - set up of the different scenario.

Scenario	Communication Costs	Internal learning: experience	External learning: spillover
Alpha	(common population)$^{1.05}$ / (standard common population)	(average common productivity) * 0.001	Yes
Beta	zero	No	Yes
Gamma	zero	0.001	Yes
Iota	zero	0.001	No

As shown in Table 1, knowledge governance costs are set to zero in the Beta, Gamma and Iota scenarios, while they are allowed to grow in the Alpha one according with the increase of each common's population. In the Alpha scenario firms have a stronger accumulation of competence that reflects both the average productivity of the common into which they are localized and its productivity peaks. In the Alpha scenario, however, firms bear knowledge governance cost that increase at a more than proportionate cost with the density of the commons, as shown in Table 2.

Table 2: Alpha versus others – population and knowledge governance costs.

Population	Alpha	Beta, Gamma and Iota
50	0.61	Zero
100	1.26	Zero
300	3.99	Zero
500	6.82	Zero
1000	14.13	Zero

The main result of the simulation concerns the comparison of the growth of productivity across the three sets of parameters. We expect that the Alpha scenario exhibits the best performances. The interpretation of the results is straightforward: i) the Beta scenario would test the generic importance of knowledge in the determining the dynamic of productivity and production, we expect Beta results to be way poorer than others, ii) the Gamma scenario would negate our hypothesis if its results were close to them of the Alpha one, and iii) the Iota scenario would underline the dramatic importance of spillover in the growth of knowledge and productivity. We see clearly, in fact, that the three alternative scenarios were not able to overcome the performance of the Alpha scenario, the single one where knowledge externalities are fully at work.

After two thousand production cycles, in the Alpha scenario, the system, as a collection of commons, reaches an average productivity of 21.46, whereas in the Gamma, Iota and Beta scenarios the system reaches, in the same number of simulation steps, respectively: 15.05, 2.02 and 0.25, as reported in table 3 and represented in figure 3.

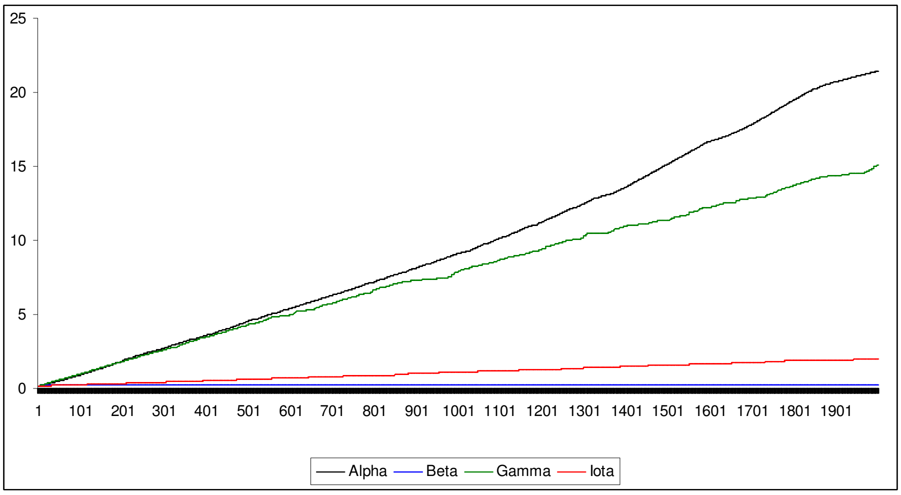

Figure 3: Alpha versus others – macro system level productivity.

As the figure 3 shows, the actual availability of knowledge externalities within each common cum the mobility of firms across commons, stylized in the Alpha scenario were able to push the whole economy to far higher productivity values.

Table 3: Alpha versus others - macro system level productivity.

Scenario	Productivity
Alpha	21.46
Beta	0.25
Gamma	15.05
Iota	2.02

Consistently the output at the macro system level shows a larger growth in the Alpha scenario than in the other ones.

Figure 4 focuses the dramatic gaps among the four scenarios, by representing the average firms output that reaches the highest level in the Alpha scenario. The Alpha scenario exhibits faster rates of growth of output and a pattern of growth characterized by the typical step-wise pattern with rates of fast growth followed by phases of slow growth. Figure 4 suggests that the growth of output levels slows when at the common level, a strong trend towards convergence seems to emerge (See Figure 5).

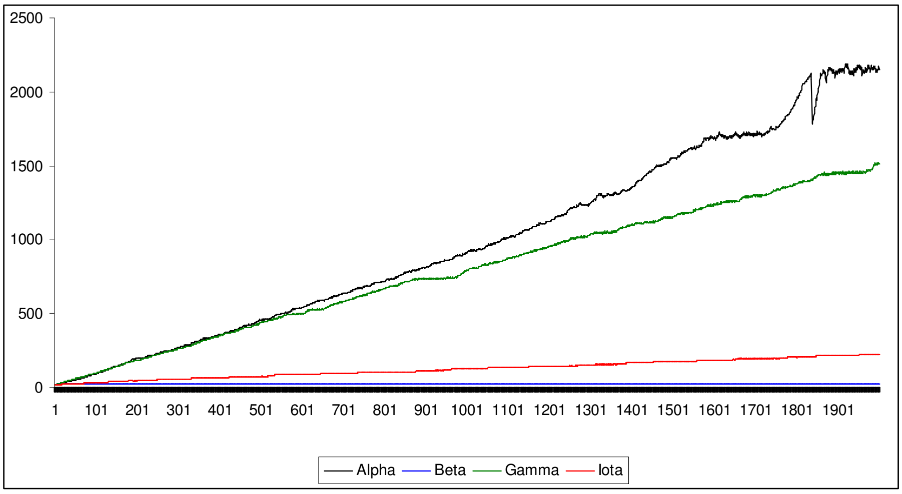

Figure 4: Alpha versus others - macro system level output.

Table 4 reports the average population and maximum population achieved during the first 2000 production cycles into the ten common the economy was divided in. The interpretation is again straightforward: the structure of the system is endogenous. A clear loop takes place between technological and structural change. We see in fact that the pace of productivity at the system level is affected by the distribution of firms across commons. At the same time however the structure of the system is affected by the different dynamics of productivity. The loop takes place through historic time and leads to strong non-ergodic path dependence. The scenario where externalities are fully at work –i.e. the Alpha scenario- shows lower levels of concentration of firms across commons. Concentration is stronger in the scenarios where the effects of externalities on competence are smaller.

The distribution of average population among commons exhibits sensible differences as shown by the row "variance": the higher the variance the greater the flows from common to common, such value is dramatically higher for the Iota scenario because there firms can not perform external learning so they react to out of equilibrium conditions by continuously moving from common to common.

Table 4: Alpha versus others – commons average and max population.

Common	Alpha		Beta		Gamma		Iota	
	Average	Max	Average	Max	Average	Max	Average	Max
1	105.82	151	71.68	94	72.49	210	82.88	235
2	82.09	158	117.88	122	56.24	172	79.28	303
3	100.36	147	174.78	193	79.18	358	86.41	418
4	92.91	158	70.16	94	92.31	394	119.49	657
5	108.58	497	125.37	155	172.79	832	82.51	325
6	108.91	185	94.83	123	154.77	641	62.95	240
7	80.25	125	27.85	95	71.19	164	51.63	194
8	100.60	170	74.18	126	122.03	651	77.72	280
9	96.80	193	111.51	130	65.64	241	267.24	551
10	100.44	282	131.65	156	112.27	506	75.22	359
Variance	100.56		1698.01		1567.57		3817.96	

The dynamics of the commons in the Alpha scenario.
The Alpha scenario represents our benchmark, validated by the results of the previous simulations. It is worth an exploration of the dynamics of structural change engendered by the model of creative response cum knowledge externalities at the common level.

At the common level the results of the simulation show that, even if picking up a new common is a blind activity for the agents –agents have no access to information about commons they not belong to-, the agents mobility strongly affects the structure of the system and the size of each common. Figure 5 provides the general representation of the phenomenon at the common level. The figure shows clearly that each common undergoes a typical schumpeterian wave with phases of growth and subsequent decline that take place along the process. The long term pattern of growth is punctuated by waves where after a rapid take-off, the common enters a contraction phase, due to the rising knowledge governance costs for excessive crowding. Whereas a common goes down others increase their size, both in terms of output and population in number of firms.

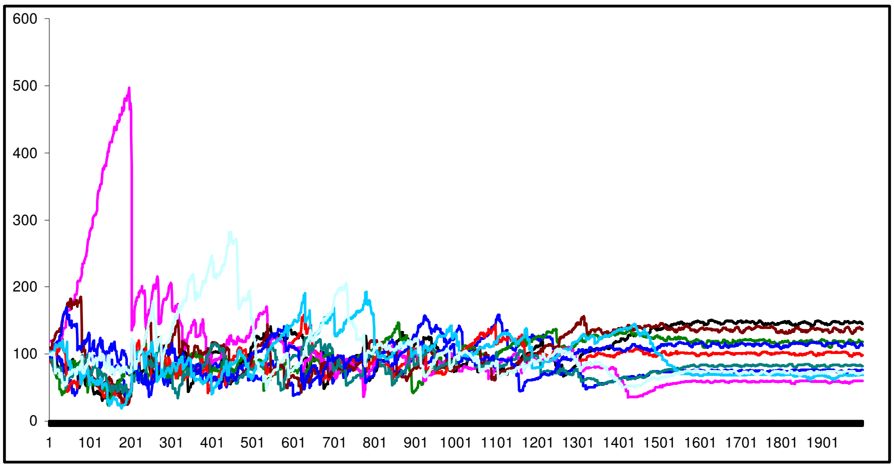

Figure 5: Alpha - Waves of population patterns across commons.

In the long term the oscillations level down and the size of the commons becomes increasingly homogeneous with a clear decline of the concentration. Variety among commons seems to exert a strong and positive effect on the overall increase of productivity at the system level. This evidence warrants further analysis but may be considered a clue that confirms the powerful effects of the replicator dynamics according to which the rate of growth of a system is positively influenced by its variety (Metcalfe 1997 2002 2007)

The schumpeterian waves at the common level affect the overall, aggregate patterns of growth of productivity at the system level with a typical step-wise pattern (See Figure 6). The evidence provided by these simulations may be interpreted as a clue that supports the view that an innovation process conceived as a schumpeterian creative reaction, made possible by marshallian externalities, engenders structural change and 'disorder' at the common level, with marked schumpeterian waves of growth of output and population of firms, but affects positively the dynamics at the system level where both output and productivity keep growing with a step-wise process. Creative destruction takes place at the firm and common levels but benefits the system at large. The locus of innovation shifts along time from one common to another with a punctuated sequence that closely parallels the long-term historic trends identified by Mokyr (1990a, 1990b, 2004).

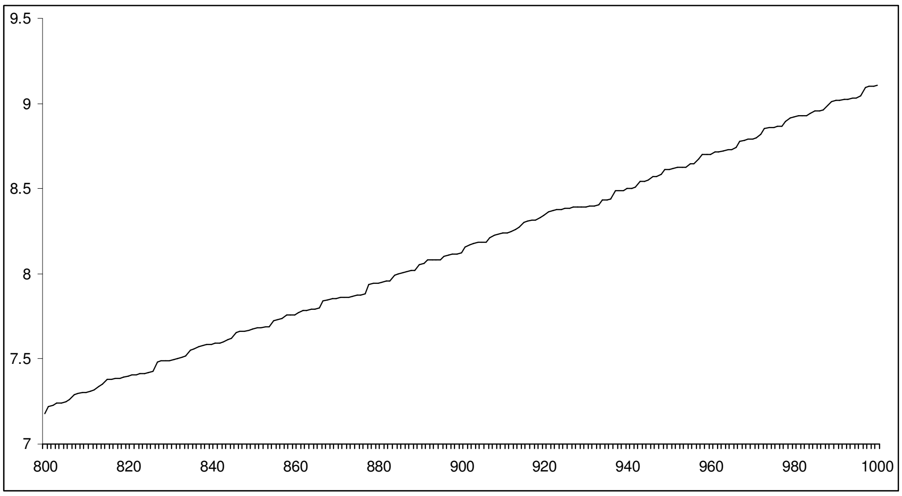

Figure 6: Alpha – macro system level productivity for cycles 800 - 1000.

Let us now explore more in details the effects of IPR regimes on the actual levels of net knowledge externalities

Influence of IPR regimes on the dynamics of centrifugal and centripetal forces.

The Phi scenario has been configured with less duration for IPR (two production cycles instead of five), in order to investigate the influence of the IPR regimes on the system dynamic and its aggregate results. Table 5 shows the data about the productivity at the macro level and the number of firms. The reduction of IPR increases the productivity levels. The reduction in the duration of patents reinforces the self feeding cycle: the larger opportunities for innovating firms to absorb the external knowledge, and combine it with the internal stock of knowledge, contribute to generate faster rates of introduction of new technologies that become public after fewer cycles and further enhance the rate of introduction of new technologies.

Table 5: Alpha versus Phi - productivity and average active firms.

Scenario	Productivity	Average active firms
Alpha	21.46	976.76
Phi	25.12	973.47

The following figure 7 shows the comparison between the evolution of the productivity at the macro system level between the Alpha and Phi scenarios.

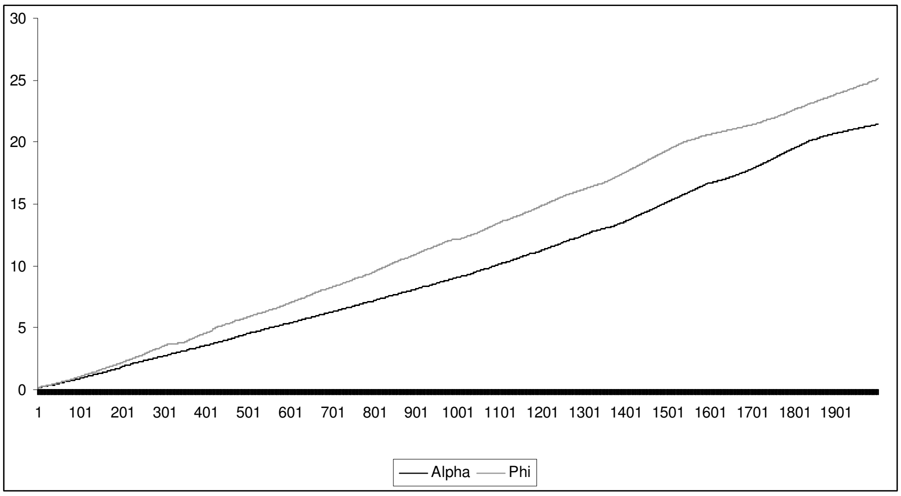

Figure 7: Alpha versus Phi - productivity at the macro system level.

In the Phi scenario the combined effect of the two main components of the knowledge externalities affects the variance of the population with a reduction of the average size of the commons and the increase of a few commons that grow and become much larger than in the Alpha scenario, where IPR protected new technologies for five cycles instead of two. Table 6 exhibits this effect by comparing the average and maximum population of each common, the Phi scenario exhibit major differences among the average commons population after 2000 cycles (see variance row in table 6) due to stronger mobility of agents across commons.

Table 6: Alpha versus Phi – commons average and max population.

Common	Alpha		Phi	
	Average	Max	Average	Max
1	105.82	151	65.19	111
2	82.09	158	73.59	146
3	100.36	147	92.81	120
4	92.91	158	99.29	303
5	108.58	497	131.44	504
6	108.91	185	162.49	229
7	80.25	125	102.91	132
8	100.60	170	72.91	152
9	96.80	193	81.80	133
10	100.44	282	91.04	134
Variance	100.56		882.04	

The evolution of the population of the commons is shown in figure 8.

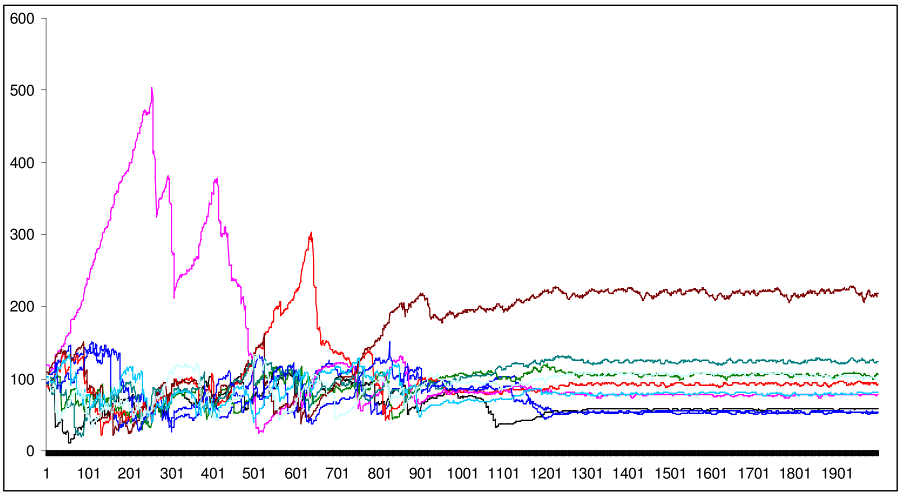

Figure 8: Phi - Waves of population patterns across commons.

These results seems to support the hypothesis that weak IPR regimes help to increasing the pace of productivity growth because they favour the dissemination of knowledge considered as a necessary and indispensable input into the recombinant generation of new knowledge. Strong IPR regimes may delay knowledge dissemination and hence the new use of existing knowledge into the recombinant generation of new knowledge.

Dynamics with different number of commons.

The last experiment is based upon the distribution of commons. The number of commons have been reduced from ten to four leaving the number of agents set to one thousand, in order to experiment the effect of a less partitioned system. The new simulation leads to the Theta scenario where at the aggregate level the results are very similar to those obtained by running the Alpha scenario. Yet the productivity achieved exhibits a slightly larger value, probably due to the fact that less commons mean better information on a larger portion of the system and fewer *Levy flights* and this supports the innovation process. Relevant data are available in Table 7 and the trend of productivity at the macro system level is reported in Figure 9.

Table 7: Alpha versus Theta - productivity and average active firms.

Scenario	Productivity	Average active firms
Alpha	21.46	976.76
Theta	22.93	983.88

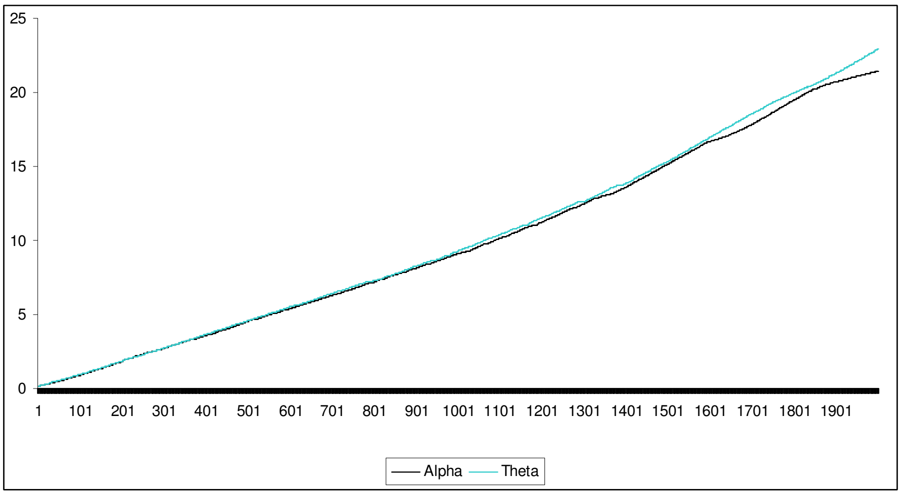

Figure 9: Alpha versus Theta - productivity at the macro system level.

Finally figure 10 illustrates the path of population evolution for each common: it confirms and exacerbates the typical Schumpeterian waves.

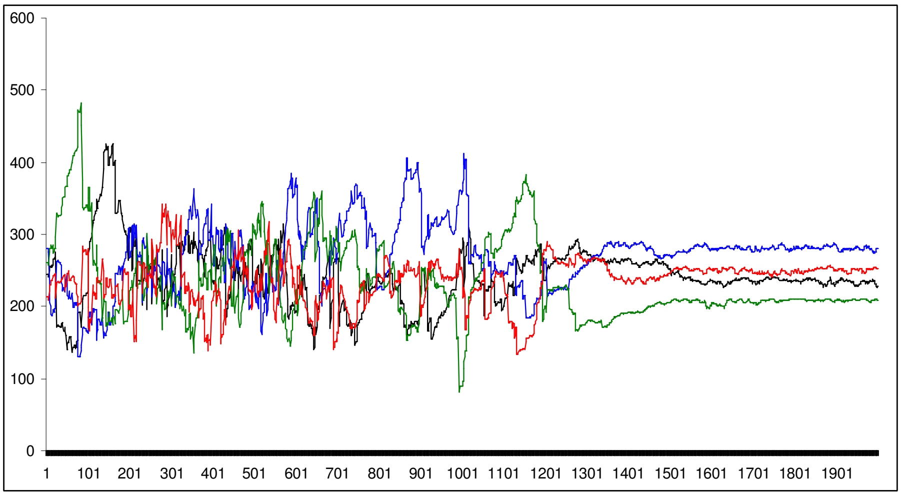

Figure 10: Theta - Waves of population patterns across commons.

5. Conclusions

Because of the pervasive role of non-appropriability, non-exahustibility, cumulability and complementarity stemming from knowledge indivisibility and non-exhaustibility, the generation, use and distribution of technological knowledge are characterized by endogenous knowledge externalities. A large body of the literature convincingly shows that the creation of technological knowledge and the introduction of innovation stem from collective and systemic efforts. These in turn emerge from a thick net of synchronic and diachronic complementarities between firms that possess complementary bits of knowledge, localized in the same region and active, linked by formal and informal ties. This literature however does not appreciate fully the changing costs and benefits of localized knowledge interactions that stem from endogenous structural changes.

The access conditions to external knowledge and the actual efforts that are necessary to take advantage of it play a crucial role in our analysis. Firms can actually generate new technological knowledge and introduce productivity enhancing innovations only if and when pecuniary knowledge externalities are available. In these circumstances, that are intrinsically localized, highly specific and idiosyncratic, innovation is the emerging property of the organized complexity of the local system.

Pecuniary knowledge externalities are external to each firm, but endogenous to the economic system as a whole. The stronger the pecuniary knowledge externalities are, the stronger are the incentives for firms to try and enter the knowledge commons where pecuniary knowledge externalities are available. Their entry affects knowledge governance costs as well as the supply of technological spillovers and changes the actual levels of pecuniary knowledge externalities. We can fully appreciate the endogenous nature of knowledge externalities as soon as we grasp the causal loop that links the amount of knowledge that each firm can generate to the cost of external knowledge available, including the levels of knowledge governance costs where the latter in turn depend upon the –changing- density of firms co-localized.

The amount of external knowledge available at any point in time and in regional and technological space is not determined once for even by exogenous factors, but strongly influenced by the conditions of knowledge governance costs within knowledge commons.

ABSM enable to articulate the relations between the basic ingredients of dynamic processes and elaborate coherent analytical frameworks that help understanding and mimic the endogenous long term dynamics of technological and structural change that are at the heart of economic growth. From this viewpoint ABSM, as a form of artificial cliometrics, has provided the opportunity to test the set of hypotheses on the role of endogenous knowledge externalities. The results of the ABSM confirm that endogenous knowledge externalities have powerful effects on the equilibrium conditions of the system dynamics at the micro, the meso and the macro levels.

At the micro-level we have seen that the reaction of firms caught in out-of-equilibrium conditions yields successful effects with the introduction of productivity enhancing innovations. Innovation is the result of the matching of the individual and intentional efforts of learning and reactive agents with the characteristics of the system into which each firm is embedded. Innovation is the emerging property of the system, where the individual action is as indispensable as the actual availability of positive pecuniary knowledge externalities. Endogenous knowledge externalities generate endogenous growth intrinsically characterized by out-of-equilibrium. The introduction of innovations, in fact, affects the transient equilibrium of product markets, exposes each firm to changes in its relative profitability and induces new innovation efforts. Equilibrium can be found only if and when innovation is impossible because of the lack of pecuniary knowledge externalities. Innovation and equilibrium are antithetic.

At the meso-level the out-of-equilibrium dynamics of endogenous knowledge externalities affect the structural characteristics of the commons and the aggregate system. Endogenous centrifugal and centripetal forces re-shape continually each common and the structure of the system, produce ever-changing heterogeneity characterized by the emergence and decline of knowledge commons. In order to access pecuniary knowledge externality, in fact, firms can move across commons. Such mobility changes the structural landscape of the each common and hence of the system, viewed as a collection of commons. Within commons the mobility across commons affects local knowledge governance costs, change the levels of pecuniary knowledge externalities and hence the likelihood that co-localized firms can actually generate new technological knowledge and introduce technological innovations that are actually able to increase their productivity. A knowledge common endowed with firms that enjoy high levels of productivity may attract many learning firms willing to improve their productivity. Their entry may affect the local levels of knowledge governance costs and reduce the actual levels of net pecuniary knowledge externalities, reducing the overall attractiveness of the location and the reduction of the aggregate dynamics of the system. Local systems may experience the transition from high levels of organized complexity able to generate high levels of net positive knowledge externalities to low levels of organized complexity where congestion and governance costs inhibit to access –economically-knowledge spillovers.

At the common level we see that the out-of-equilibrium process leads to non-liner patterns of economic growth characterized by significant oscillations in the levels of population and in the rates of growth of output, profitability and productivity that take the typical form of long waves, familiar to the Schumpeterian analysis of business cycles.

At the system level, the dynamics of productivity growth exhibits a typical step-wise pattern with long periods of times characterized by smooth rates of increase and sudden and sharp jumps. When the distribution of firms within knowledge commons happens to be highly effective and the local system can engender high levels of knowledge externalities, the rates of generation of new knowledge increase, hence the rates of productivity enhancing innovations is augmented. At the aggregate level the system experiences fast rates of growth of output and productivity. When, on the opposite, the distribution of the firms across knowledge commons reduces the opportunities to benefit of net positive knowledge externalities, crowded knowledge commons command high levels of knowledge governance costs and peripheral knowledge commons with low levels of productivity supply low opportunities for knowledge dissemination, the system experiences low rates of introduction of innovations and hence of productivity growth.

The endogenous dynamics of knowledge externalities engenders multiple equilibria as well as micro-macro feedbacks such that the dynamics of the system becomes very sensitive to small and unintended shocks. When there is a single attractor, prices can perform their function as vectors of reliable signals about markets conditions and competition can restore equilibrium conditions. When, on the opposite, in a dynamic context based upon out-of-equilibrium conditions, the consequences of individual action on the structural characteristics of the system are difficult to foresee as much as the introduction of innovations and their consequences on the profitability of each agent, only procedural rationality can apply in local context and with a short time span. No countervailing force can identify the true attractor. Entrepreneurial action hence may exert major consequences at the economic system level with either positive or negative effects.

Variety across firms and commons and enhanced knowledge dissemination exert positive effects on the macrodynamics of the system and confirm the powerful effects of the replicator dynamics.

With a proper map of the system, the intentional change of the parameters of the system carefully executed by policy interventions can exert long-lasting positive effects both with respect to the structure of the knowledge commons and the general productivity levels. Intentional changes brought about by well calibrated policy decisions, aware of the endogeneity of knowledge externalities, can stimulate the reaction of firms and their strategic decision so as to increase the generation of technological knowledge and innovate with long-lasting positive effects.

In this context the issues of dynamic coordination among agents and institutions becomes most relevant in order to assess the general outcome of each single action. The past dependence exerts a strong influence, yet, it is not the single factor at work: at each point in time firms can change the amount of resources invested in the generation of knowledge, new governance mechanisms can be introduced, the mobility of firms across the knowledge and regional space change the structure of the system and hence the levels of pecuniary knowledge externalities.

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