From techno–scientific grammar to organizational syntax:
new production insights on the nature of the firm

Riccardo Leoncini*
Mauro Lombard†
Sandro Montresor‡

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Abstract

This paper addresses the problem of the role of technology for the
firm’s organization. In particular, it aims at showing how the role of
production in investigating the existence, boundaries, organization and
dynamics of the firm can be better understood through a two-fold multi-
disciplinary exercise: on the one hand, by drawing on engineering a
more accurate description of the production process itself, which helps
figuring out its inner complexity and potentially explosive nature; on the
other hand, by referring to computational linguistics for a deeper ac-
count of the nature of economic agents and of those mechanisms through
which they are able to make what is potentially explosive actually or-
dered. In order to fulfil this aim, we will set the production process
within a complexity framework, resulting from the dynamic mapping
across different, multiple spaces of search. In this way we will furnish

*Department of Economics, University of Bologna (I). E-mail: riccardo.leoncini@unibo.it
†Department of Economics, University of Florence (I). E-mail: mauro.lombardi@unifi.it
‡Department of Economics, University of Bologna (I). E-mail: sandro.montreso@.unibo.it
a novel vision of the firm as a set of emergent properties at the dynamic interweaving of stability and variability, simplicity and complexity, orderly and chaotic behaviour. The nature of the firm will thus come to be defined in terms of production possibilities that are constructed by, on the one side, the human attitude towards pattern seeking activity, and, on the other side, a push-and-pull non-linear mechanism that forces the emergence of firms at the edge of chaos.

1 Introduction

For quite a long time, the issue of the “nature of the firm”, as Ronald Coase termed the basic ontological questions of the economics of the firm (Coase 1937), has remained a contractual kind of issue, mainly addressed by referring to the properties of the transactions the “homo contractualis” carries out and to his behavioral traits. Although the emergence, in the ‘80s, of the strategic management view based on resources and competences, and its theoretical pairing with evolutionary economics (Montgomery 1995), spurred an important rethinking of the production side of the firm, the two worlds of transaction and production kept on developing quite separately, determining a sort of “production–transaction dichotomy” (Montresor 2004).

In the ’90s, a deeper analysis of the role of technology for the firm’s organization, and of the latter for the former, has started what could be called “the re–birth of production in the theory of economic organization” (Langlois and Foss 1999). In this last respect, important results have been obtained since then, the most remarkable of which are for sure represented by the massive literature on the relationships between production and organizational modularity (Brusoni, Prencipe, and Pavitt 2001). Still, after more than 10 years, such a re-birth appears at its initial stages, and the full implications on the nature of the firm are largely undiscovered yet.

In trying to fill this knowledge gap, the present paper aims at showing how the role of production in investigating the existence, boundaries, organization and dynamics of the firm can be further appreciated and better understood through a two-fold multidisciplinary exercise: on the one hand, by drawing on engineering a more accurate description of the production process itself, which helps figuring out its inner complexity and potentially explosive nature; on the other hand, by referring to computational linguistics for a deeper account of the nature of economic agents and of those mechanisms through which they are able to make what is potentially explosive actually ordered.

In so doing, not only will we be able to tackle those intriguing problems, which are at the center of the contemporary economics of the firm, such as the
dynamic interweaving of stability and variability, simplicity and complexity, orderly and chaotic behaviour. But we will also provide some novel insights on the nature of the firm, which both theoretical and empirical research in the topic should try to combine with more standard contractual kind of explanations. Indeed, how such an integration could be implemented, leading to the view of the firm as a manifold coordination mechanism, will not be addressed in the present paper, and rather represents one of our future research questions.

The paper is structured as follows. Section 2 starts by proposing a sketchy, interpretative view of the “Process of Product Development” (PDP) which can account for the inner cognitive, complex and dynamic nature of production. PDP is actually viewed as a “Global Workspace for Producers” (GWP), which unfolds as a set of multi-layered problem solving activities. These, in turn, are developed through search activities in those multiple spaces which refer to design parameters, engineering characteristics, component and product properties, and through the dynamic mappings among these search spaces.

Such an interpretation makes of production a truly complex process which, in the presence of high-dimensionality of the search spaces, runs the risk of ending up with a combinatorial explosion of the results. Still, an appropriate integration of the bounded rationality description of the economic agents, which draws on computational linguistics the use they make of such fundamental properties of “compositionality” and “recursiveness”, is able to explain how stable designs and organizational configurations are able to emerge even in this chaotic instances: a point which is addressed in Section 3.

Far from being an unduly complication, the engineering view of production we propose in the paper brings to the front the role of dynamic mappings between different spaces and sub-spaces as fundamental components: not only in determining product complexity, but also and above all in shaping a new coordination mechanism among economic agents which strictly pertains to the world of production, rather than transaction. Dynamic mappings in fact occur through “information packages”, unceasingly fed by data and knowledge flows, which constitute the embedded coordination mechanism within products and organizations. What is more, as these information packages develop through and across changing networks of interdependencies, the analysis of PDP and of the structure of GWP provides us with important insights also in terms of firm boundaries and organizational structures: in other words, as we argue in Section 4, it adds new production insights on the nature of the firm.

Last but not least, the mapping between different search spaces and sub-spaces clearly portraits also the inner complexity of the firm dynamics. More precisely, as we argue in Section 5, such a representation turns out extremely helpful in operationalizing a complex view of dynamic capabilities, which we
have developed elsewhere (Leoncini and Montresor 2008), according to which the firms’ capacity to deal with change can be traced back to their capacity of combining the re-mapping of their search spaces with their reconfiguration, depending on the nature and magnitude of the change itself. Some final remarks and future research developments conclude the paper.

2 “Opening the production black-box”: the product development process

Important literature, either in economic and engineering domains of research, converges on viewing production processes as nested systems of multiple sequences of search activities. On the basis of theoretical results obtained by many studies, Buenstorf (2005) debates the evolution of interdependencies within the production process, first of all by focusing on potentialities and problems inherent to the complex systems. From a complementary point of view (Nightingale 2000) sharpens the process of development of a product as hierarchy of increasingly specific sub-problems and a corresponding set of problem-solving tasks.

The PDP can be broken up into sub-systems and subcomponents. In this way a “pyramid” of problem solving tasks for systems, subsystems and components mirrors the physical structure of the product. From this point of view the design process “for devices that constitute complex systems” is “multilevel and hierarchical” (Vincenti 1990, p. 9). Design processes can be temporal and iterative, depending on the uncertainty of different types of contexts (economic, technological, institutional), and at the same time feedback loops can arise. Decision variables and determining environmental factors are technological uncertainty, complexity of product, degrees of freedom within products as systems, set of solved or unsolved problems, organisational configurations.

Looking more precisely at the production process means analysing first of all the product development process, from the initial (i.e. a good as a vector of desired attributes) to the final state (i.e. a real commodity with given characteristics). The traditional engineering approach conceives PDP essentially as a sequence of stages: planning, specification design, implementation, and testing (Bar-Yam 2002). Since the complexity of products, especially for large engineering projects, increases as a consequence of growth of interdependencies among components of a system, the problem is mainly tackled by means of relevant strategies: modularity, abstraction, hierarchy and layering. This implies viewing a way out such as incremental engineering, but it is not enough as Bar-Yam (2002, appendix 1 and 2) argues because two systemic laws (requisite
variety, functional complexity) found the statement that “for all practical purposes adequate functional testing of complex engineered systems is impossible” (Bar-Yam 2002, p. 4). So a complex system approach to innovation has to be developed toward an evolutionary engineering, which is instead based on a very different environment: multiple small teams, redundancy and parallelism, variety of possibilities and sub-systems.

This perspective does not prevent experts from viewing PDP as an iterative and incremental process, but it is mainly “an intricate set of interconnected tasks carried out by hundreds of engineers” (Braha and Bar-Yam 2007, p. 1127), where network structure, interdependencies and design iterations are fundamental ingredients. From this point of view, we can deduce that network topology is fundamental for the information flow and thus for its dynamics: asymmetries among agents, inhomogeneous distribution of information and their role in propagating it among interacting components are all essential characteristics which determine the pattern of coordination, that is how the final product emerges in consequence of the role exercised by system integrators. PDP and structural properties of complex networks are then tightly linked and their analysis is useful for understanding techno-economic dynamics.

It is thus not surprising that both design process and PDP are viewed as scientific problem-solving (Braha and Maimon 1998), the dynamics of which shows basic properties: stepwise, iterative, evolutionary transformation process. Indeed from an initial idea to its final concrete realization, ready to market, a variable number of requirements have to be satisfied: functionality, reliability, modifiability, performance. The process is stepwise as sequential phases have to be crossed, while information flows (new data and knowledge, changing constraints, need for refining details and basic elements) require going back and executing again given steps (feedback loops, iterated cycles). The evolutionary nature stems from this: purposeful agents, either alone or grouped, compose adaptive systems and sub-systems as they exchange information in searching for solutions fit for goal-seeking operations. Therefore feedback loops and interactions can occur through (and are expressed by) the variable topology of networks. Different design paradigms have been developed and are used by scholars and experts.\footnote{The most widespread paradigms are: ASE (Analysis-Synthesis-Evaluation), Case-Based, Cognitive, Algorithmic and Artificial Intelligence, Creative Design (SIT, Structured Inventive Thinking) See, for example, Braha and Maimon (1998) and Dasgupta (1989).}

In general, PDP starts from abstract specifications of parameters, that is a vector representing the demand requirements (customer needs, CNs), then translates them into functional requirements (FRs), which have in turn to be refined through iteratively searching for better solutions to “structure” prob-
lems. We call these design solutions (structural descriptions or SD), (Braha and Reich 2003). The term structure refers to information concerning the relationships between components or parts (modules) of a product, so that adequate values are satisfied for a determined function.\(^2\)

These values have to match with parameters concerning process variables (PVs), related to the realization sequence. So we have four vectors, each of them representing evolving sub–sets of a global workspace, which spreads from product characteristics to process variables. This representation allow sus to view the PDP as sets of problem solving activities and searching through multiple state spaces, thanks to multiple exploration procedures aiming at finding congruent solutions, each of them belonging to different sub–spaces (CNs, FRs, SDs, PVs). Ideally explorations should terminate with a set of solutions, but these latter only exceptionally are the results of one-to-one mapping and more often the unpredictable outcomes of many-to-many mapping, executed by purposive agents within goal–seeking operating units. In this way it seems well founded to view the global workspace as populated with different purposive organisations acting as adaptive systems. An important point must be stressed: if a product has an integral architecture (Ulrich 1995), i.e. an integral arrangement of its components, it will probably be easy to find a good global solution. If the product shows some degree of complexity and the environment (techno–scientific, economic) is dynamic then there is an almost certain risk of facing a combinatorial explosion in searching for solutions within the multiple sub–spaces. In this case a product can be decomposed into sub–systems, modules, components (Mikkola 2006), with different and variable degrees of coupling. A relevant problem arises: how is it possible to find a good or even an optimal solution, above all when many — either individuals or grouped — agents interact?

In tackling the question our starting points are: 1) individuals are “adaptive and intelligent agents with bounded information processing capabilities (Carley 2002); 2) these capabilities are goal–oriented in the sense that agents are able to change goals on the basis of interactions with other agents, the environment and information flows (Carley and Newell 1994).

Given this characterization of human beings organizations are “complex adaptive systems, composed of intelligent, task–oriented, boundedly rational and socially situated agents and faced with an environment that also has the

\(^2\)“Function is the relation between a goal of a human user and the behaviour of the system. Structure is defined as the information about the interconnection of modules, organised either functionally, how the modules interact — or physically — how it is packaged; behaviour can be defined as the relationship between input from the environment and the output of affect the component usually interfaces to the environment” (Braha and Maimon 1998, p. 59, following Bobrow, 1989).
potential for change” (Carley, M.J., and Lin 1998).

These assumptions induce us to view a product as a complex system, within which we define embedded coordination as the arrival point, when reciprocal coherent functionalities are found by adaptive agents. In this perspective the PDP is a self-organising system inasmuch as changing interactions among components alter the internal structure of an organization and thus influence the pursued functions in response to environmental variable conditions.

As a matter of fact we can hypothesise that the exploratory activities within multiple spaces can give rise to two ideal “extreme” prototypes. The first occurs when the path from CNs to PVs is well-defined, because problems are well-structured and solutions can be easily found thanks to a more or less rapid research in each sub-space. Let us call this situation a “platonic model” in order to capture a universe characterised by “clear and distinct ideas” (Figure 1). In the platonic world interactions among agents and their groupings are at their minimum, while exploitation of existing knowledge prevails on exploration in multiple directions. The possibility of vertically integrated activities within the PDP process (in other words vertical organization) is clearly linked to his type of horizon, where mapping between function, structure and behaviour can be scheduled on the basis of sound basic knowledge.

What happens when ideas are muddled or fuzzy, problems are ill-defined and then solutions are not within reach? In this situation we need to explore

\[ \begin{array}{cccc}
CN_1 & FR_1 & SD_1 & PV_1 \\
CN_2 & FR_2 & SD_2 & PV_2 \\
\vdots & \vdots & \vdots & \vdots \\
\end{array} \]

Global workspace

Figure 1: Ordered world: STS, Platonic world, one-to-one mapping

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3The dimensions to be analysed are known and the connections among them are under control.
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different domains of research by activating networks of goal–seeking entities, which adaptively search for locally and globally coherent values to be assigned to modules, components and so on. Therefore refinement and specification processes come to the fore, while it is necessary to keep in mind that a changing topology of networks becomes fundamental. Indeed as the complexity of the product increases the evolving morphology of the network implies increasing dimensionality of search processes, as individuals and groups follow different research trajectories and exchange information. In this way new information can be acquired and new combinations of knowledge can be tried and tested at many levels, depending on the decomposition of the process (Figure 2). But feedback loops, iterations and different degrees of coupling can quickly give rise to the combinatorial explosion and to the subsequent impossibility to define the final vector of attributes.

Figure 2: Disordered world: feedback loops, iterated cycles, random signals and information flows, many-to-many-mapping

Let us summarise the question. We are facing two prototypical representations of the PDP: 1) the former in centred on a system almost perfectly known; we call them semantically transparent systems (STS); 2) the latter is characterised by incompleteness of knowledge and by a growing complexity of exploratory activities, executed within an evolving topology of networks. We call them combinatorial systems\(^4\) in order to focus on their capability of

\[^4\text{We draw on (Licata 2003) the conceptual distinction between STS and CS, but it must be emphasised that the term CS is not derived from the original source, where Licata develops an extremely interesting approach to the analysis of dynamic systems. Particularly he treats the so-called logically open systems, which constitute fundamental components of “n-order” cybernetics.} \]
exploring search spaces by means of either combining or re-combining available chunks of information and knowledge (generative combinatorics), so that radically new concepts and theories can emerge (creative combinatorics).

STS are based on perfectly known data structures and syntactical rules, which specify how elements have to be combined. In other terms STS are symbolic representational models, which explain the working of a given system and allow us to schedule it in searching for appropriate values of function, structure, and behaviour.

Instead CS have different properties: parallel information processing, non linear dynamics and high-dimensionality as the topological structure evolves in consequence of information flows and signals arriving from many sources or domains. In this way creative combinatorics can prevail and produce novelties at a theoretical and an empirical level.

A huge amount of literature has focused on the nature and type of information flows in order to understand influences on firm’s configurations. Depending on how information and knowledge are created and transmitted we have “traditional sequential development, overlapping problem solving, and modular product development” (Sanchez and Mahoney 1996). Within a scenario riddled with increasing product variety and techno-science changes an imperative for economic units is to adopt a modularity approach to PDP and to organization models of firms (Mikkola and Gassmann 2003, Sanchez and Mahoney 1996, Baldwin and Clark 2000). Then as the decomposition of products and modular network structure (Sturgeon 2002) unfold different patterns of modularity emerge, linked to how exploration, information-processing and transmission are implemented thanks to changing connective geometry among agents.

How does “order” arise” in a “non platonic world”? In other terms, how can many-to-many mappings between only partially known search spaces converge on a precise vector of final attributes? This should happen while many goal-seeking operations are tried and verified by exploring different domains.

A possible trajectory could be indicated through postulating the existence of a kind of endogenous steering mechanism, based on widespread evaluate-and-test behaviours among adaptive units. Feedback loops, iterations cycles, and exchange of information should act as measuring devices by inducing adaptive systems to change goals and try again until coherence is attained.

But what conditions trigger processes leading to coherence, which means congruent parameters selected from complex many-to-may mappings?

The line of research we propose lever the concept of protocols, which are employed in analysing the product architecture 5 and more in general the re-

5Mikkola (2006, p. 133) defines protocols or interfaces as “linkages among components
relationships and processes between modules belonging to evolutionary systems (Csete and Doyle 2002, Kitano 2002). To our purposes one point is essential: protocols are rules that prescribe “recipes, architectures, rules, interfaces, etiquettes, and codes of conduct” (Csete and Doyle 2002). In this way they are fundamental in order to allow complex systems to acquire essential properties such as: spiralling robustness, layering, signalling fragility, metastability.

From our perspective viewing protocols in terms of rules must be stressed, because they can be viewed as the results of multiple exploratory activities, executed by adaptive agents. Where do they come from?

3 Emerging order: rules from complex mappings between different sub–spaces

Rules play an important function within the research line centred on agents with purposeful behaviour based on programs. These latter are pre–arranged information, or conjectural knowledge about the world (Vanberg 2002, p. 15), which is unceasingly changed depending on encoding information acquired by interacting with the environment. Lessons from experience and processed information are stored in forms of instructions (conscious or unconscious “if . . . then” rules), which are used in ever changing problem solving activities and thus are subject to unforeseeable transformations, on the basis of decoding activity, performed either by the same agents or by whatever other interactor. The sequences of encoding, based on feedback processes, and decoding, centred on applying elements of a repertoire of programs, are the gist of the adaptive dynamics and the adaptedness property of human behaviour, as successful programs or set of rules are retained while those totally or partially failed lead to changes or neglect. Past experience — synthesised in recipes, rules or programs — constitutes the fundamental ingredient of a problem solving activity, viewed as unceasing search for similarities between past situations and the task environment. In the analysis of the innovation processes Van de Poel (2003) defines the “technological regime” as “the rules that guide the design and further development of a particular technology” and describes a hierarchy of rules: “core rules”, which are “abstract and generative guiding principles” founding a technological regime, and “peripheral rules”, which concern design modules, and sub–systems of product architectures”. Csete and Doyle (2002) define protocols “as rules designed to manage relationships and processes smoothly and effectively”.

It is in the form of “If . . . then rules which may reach considerable degrees of complexity” (Vanberg 2002, p. 16).

Decoding is about how programs are implemented, in or applied to, particular choice situations” (Vanberg 2002, p. 16).
activity and specification work up to the final artefact. Van den Ende and Kemp (1999: 835) define a technological regime “as the grammar or rule-set embedded in the coherent complex of a technology (or mode of manufacturing) which structures the search activities of engineers and the policies and actions of other technology actors (including public authorities)”. In a world populated with adaptive agents with bounded information processing capabilities, it is precisely knowledge that is the source of embedded coordination, since it is “a complex structure of ideational kernels and the connections among them” (Carley 2002, p. 7258). Ideational kernels are in turn the basic building blocks of science and technology, where these are called “executable” (Arthur and Polak 2006).

We can sharpen this line of research so that rules are the outcomes of dynamic mappings between multiple search spaces (Lombardi 2008)(Lombardi 2009, forthcoming): dynamic mappings can avoid combinatorial explosion, even if they are executed by many groups of agents, thanks to two basic principles: compositionality and recursiveness. Human beings have evolved as pattern seekers in searching for ordering principles, due to self-structuring information processes (Tononi, Sporns, and Edelman 1996, Tononi, Edelman, and Sporns 1998, Lungarella and Sporns 2005). They have an evolutionary founded propensity to discover statistical regularities within a world full of conflicting and unpredictable signals and events. So the compositionality principle implies that, even during the most chaotic or random many-to-many mappings, agents unceasingly discard meaningless or completely random signals (lost information); instead they tend to capture associations and links (acquired information). In this way rules are “discovered” (created) and mapping between many sub-spaces become structured, by creating interlinked statements concerning the world around us. Therefore the propensity to order the real processes is tightly linked to the evolutionary bias towards associating components of our neighbourhood and structuring them, be it local environment, social conditions, technology, product design.

Compositionality, which is a basic property of human language, is not alone, because it is intrinsically intertwined with recursiveness, i.e. the propensity to create nested systems and sub-systems (Figure 3). The proposed theoretical frame founds the general statement that mutual adaptation among different social groups and structures of interactions among them lead to the formation

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8Arthur and Polak (2006, p. 23) define technology as a "combination of executables", which are means fit for fulfilling a purpose or execute a function. Technologies are sets of "components, or assemblies, or subroutines, or stages", each of them executes a function or pursues a purpose. Thus “a technology is organized in a loose hierarchy of groupings or combinations of parts and subparts that themselves are technologies.” (Arthur 1989, p. 277).
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Figure 3: Compositionality and recursiveness

of hierarchical rules and grammar, which are the embedded coordination of the socio–technical regimes (Geels 2005).

4 Towards a production–based account of the nature of the firm

Which are the implications of this way of looking at production for the nature of the firm? What does the analysis of PDP and GWP add to what we know from the contractual perspective and from the competence based views of the firm? As we will see in the following, some novel insights emerge which candidate for what we could call a “production–based account of the firm”. In other words, our production analysis, per se, provides sufficient arguments to address the basic questions about the nature of the firm. This does not mean that other more standard explanations should dismissed, but rather compared and possibly integrated with it, a task we set by now in our future research agenda.

4.1 The production nature of the firm

At the outset, the firm which emerges from the PDP analysis we have described above is clearly at odds with the standard one as a compact unit of analysis. Indeed, the latter idea can be retained if and only if the production process is assumed to occur in a ‘newtonian world’, characterized by: i) uniform or homogeneous behaviors, for example the constrained maximization principle; ii) no limitations in information processing and absence of noise and friction.
(Boisot and Canals 2004, p.49); iii) completely known production functions for all goods. In this world there is symmetry in space and in time, inasmuch as homogeneous actors (‘representative agents’ or prototypical economic units) make decisions on the basis of perfectly known variables.

On the contrary, the GWP is definitively a non–newtonian world, populated by economic agents whose decision-making is a different mix of Cartesian behaviour — that is, the ability to “exploit the available information” — and stochastic behavior — that is, the ability to go “beyond the present knowledge” (Allen and Lesser 1991): in other words, a world of ‘broken symmetry’ (Anderson 1972) characterized, first of all, by the in–homogeneity assumption. Furthermore, the GWP is non–newtonian also because the search activities which occur in PDP are marked by the stochastic idiosyncratic assumption, that is the economic equivalent of the natural science one according to which a “particle of microstate behaviour is assumed to consist of idiosyncratic microstates which have some probability of occurrence” (McKelvey 1999).

A crucial implication of this non–newtonian world of production is that the firms which populate it are aggregates of components, that is variable combinations of elements to be defined in relation to information flows which are necessarily incompletely known. Accordingly, a production–based analysis of the firm first of all requires a decomposition of the compact basic unit of the newtonian world, bringing to the front those multiple goals and problem–solving activities which emerge in different operating environments. Even by neglecting, at least to start with, the complex issue of the firm’s stakeholders, and of their possibly conflicting economic aims and incentives — that is the contractual nature of the firm — production as such thus poses problems of coordination which are usually relegated to the world of organization.9

This emerges clearly when the complexity of a product, and how to measure it, is explicitly considered.10. Following this line of research, coordination in fact turns out to be, first of all, an issue of “managing dependencies among [production] entities” (Malone, Crowston, Lee, and Pentland 1999). What is more, it is coordination in production which then affects coordination in organization, as there are dynamic relationships between the evolution of organizational capabilities, on the one hand, and the structures and the type of architectural design on the other (Gulati and Eppinger 1996). To put it simply, the com-

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9What is more, as the production environment is continuously fostered by exogenous and endogenous mechanisms, the same coordination problems are intrinsically dynamic, a point on which we will return in Section 5.

10Complexity has been defined by referring to three elements: “(1) the number of product components to specify and produce, (2) the extent of interactions to manage between these components (parts coupling), and (3) the degree of product novelty” (Novak and Eppinger 2001, p.189)
plexity of products, viewed as product architecture (Pimmler and Eppinger 1994, Browning 2001), crucially affects that of the organizational structure. First of all, decomposition choices in production affect dependencies, interactions, functional differentiation, competences development, and managerial decision processes. Second, technical capabilities are linked to the layout of product architecture, because the arrangement of different pieces influences the pattern of information exchanges, the pathways towards specialization and its changes. At the same time the interdependence between product architecture and organizational design means that ‘product architecture influences the way firms learn’ (Yassine and Wissmann 2007).

Following the GWP view, not only does production pose coordination problems, but it also embodies production–based coordination mechanisms. Indeed, goal–oriented activities are distributed and coordinated on the basis of information processing, but this time occurring within physical and energetic processes. The morphologies of mappings and connections among the PS activities we have investigated in Section 2 actually define what we could call behavioural patterns, meant as different models of how people and adaptive units interact in exchanging information and executing operational function. Once more, this coordination mechanism is inherently production–based, and should be clearly distinguished from its organizational counterparts, that is ‘organizational routines’ (Nelson and Winter 1982) and ‘dynamic capabilities’, often meant as ‘meta–routines’ (Winter 2003). And the difference is precisely the one which exists between creating mechanisms and results: morphology of networks foster dynamic capabilities, part of which can be partially static and most of them are “complex, structured and multidimensional” (Winter 2003, p. 992). Of course, this does not entail that behavioral routines do not work as governance instruments (Coriat and Dosi 1999). But rather than the firm is a manifold coordination mechanism within which behavioral patterns play an equally important role.

4.2 The production boundaries of the firm

Looking at production through the PDP perspective also provides us with some new insights about the boundaries of the firm, and about the crucial “make-or-buy” issue which determines them.

The starting point in this last respect is the fact that, as we have argued in the previous section, from a production–based perspective, firms can be envisaged as variable sets or systems of elements, composed of goal–oriented adaptive units, depending on the unrolling of PS activities. This affects directly the firm’s boundaries, as the same adaptive units develop complementarities and interdependencies, not only among them, but also with respect to the external
environment. Consequently, as interaction and reinforcement occur (Siggelkow 2002), internal fitting and external matching, rather than internal “misfitting” or external mismatching, emerge, depending on the potential conflict between the changing environmental requirements and the evolving properties of firms. In this production perspective, firms are thus open network configurations, made up of nodes and edges (interactions), with extremely variable degrees of freedom: vertically organized, tightly and loosely coupled. And on these degrees of freedom, strictly related to the world of production, in turn depends the setting of the firm’s boundaries.

Once the firm is conceived as such kind of network, the implications that we get for vertical integration and disintegration decisions turn out to be quite at odds with those which follow from a purely contractual perspective. Indeed, the simplest case is this time that “at the beginning there was the firm”, and not the market, as in the Coasian perspective. The first of the two extreme prototypes of production organization we have sketched in Section 2, that is the “Semantically Transparent Systems” (STS) which hold in the platonic world, naturally calls for a fully vertically integrated organization of production. When the dynamic mapping from CNs to PVs is well–defined, as problems are well–structured and solutions easily found, exploitation of existing knowledge prevails on exploration in multiple directions. Accordingly, external networking through buy and/or outsourcing strategies is not necessary, at least from a technological and production perspective: if economic and contractual arguments call for them, is instead another story, which should of course be related to our own story.

What does justify the market then, or better to say vertical disintegration? The answer can be found in the other of the two PDP extremes, that is in what we called the “Combinatorial Systems” (CS). As we said, in this non–platonic world (where ideas are muddled or fuzzy), problems are ill–defined and solutions out of reach. Accordingly, networks of goal–seeking entities should be activated which adaptively search for locally and globally coherent values to be assigned to modules, components and so on. Outsourcing and disintegrating thus becomes essential in order to explore different domains of research, as only in this way new information can be acquired and new combinations of knowledge can be tried and tested at many levels, depending on the decomposition of the process (Brusoni, Prencipe, and Pavitt 2001). Overturning the standard conclusions of the industrial organization literature on the topic (Robertson and Langlois 1995), according to which vertically integrated structures has a natural comparative advantages in dealing with the complexity of radical innovations, in our production–based approach a vertically disintegrated structure is the one through which complexity is managed, through refinement and specification processes. As we said, in so doing, the topology of networks changes.
In particular, as the complexity of the product increases, the evolving morphology of the network implies increasing dimensionality of search processes, as individuals and groups follow different research trajectories and exchange information. Feedback loops, iterations and different degrees of coupling can quickly give rise to the combinatorial explosion and to the subsequent impossibility of defining the final vector of attributes. Nonetheless, as we also said, compositionality and recursiveness prevent this from occurring.

Paralleling the Coasian logic, in-between the STS and CS “prototypes”, the GWP “true-type” appears a mixture of vertically integrated and disintegrated production structures, depending on the actual definition degree of the dynamic mapping from CNs to PVs. Unlike the Coasian tradition, however, the boundaries which separate the firm from its outer environment never get crystallized in a “marginal” search–activity (as a sort of counterpart of the “marginal” transaction). On the contrary, they remain “permeable” and fluid in order to allow for the more efficient use of the GWP knowledge (Jacobs and Billinger 2006), so that make-and-buy the same activity — that is searching and mapping both internally and externally — turns out as a viable solution to the make-or-buy dilemma. This follows directly from the inherently dynamic nature of the mapping processes through which PDP develops, an issue to which we move in the next section.

5 The organization of the firm in front of innovation: dynamic capabilities

5.1 The firm as a complex adaptive system

As we said, the production–based view of the firm that endorse makes of it a complex system. What is more, the dynamics of the firm so conceptualised is an adaptive kind of dynamics that such complex systems follow. In principle, the idea might appears not new. Indeed, an increasing number of contributions has started showing that firms (and more in general organisations) actually present the traits of a wide range of open systems in natural and physical worlds, whose ‘adaptation’ to their hosting environment resolves in a ‘complex’ process of evolution/co–evolution. Far from equilibrium systems (Prigogine 1976) can therefore experience a sequence of phases in which the so called ‘edge of chaos’ — a ‘transition phase’ from a highly ordered phase to a chaotic

one — describes a situation in which the degree of fitness between an open system and its environment is maximum (Kauffman 1995). By conceiving firms as adaptive complex systems, it is possible to interpret their ‘emergent structures’ in terms of the degree of internal order (i.e. as a dynamic balance of its internal degree of ‘order’) maintained by exporting entropy towards the environment (see for example Fuller and Moran (2001)).

Endorsing such a metaphor in interpreting the firm dynamics is at this point a sort of translation exercise suggesting that these inner determinants can be directly related to the dynamic capabilities of the firm, and in a way which allows us to address the several aspects involved in deciding about production processes. The starting point of this argument is the idea that the non-linear firm dynamics can be sketched as a process triggered and fuelled by the intertwining of two factors:

1. The threshold level in the firm response mechanisms to environmental flows. This factor can be seen as the determinant of a homeostatic mechanism which calibrates the system’s behaviour in order to keep the maximum level of stability in front of ‘sufficiently small’ environmental fluctuations. If the relevant environmental signals overcome a certain threshold level, a process of structural change is engendered.

2. The relative balance between environmental ‘turbulence’ and inner ‘entropy’. This factor is less obvious, and it needs some further elaboration. Although in evolutionary modelling, agents relate with the environment undergoing a process of selection that picks up the fittest, in our case the relative dimension of the relationships firm/environment can assume quite different specifications, as the process of evolution that firms undergo depends on the ‘relative’ dimension of the environment, rather than from its absolute dimension. Indeed, firms can have quite different dimensions in terms of their environment, as it is fairly obvious that differences in sectoral specificity, technological regimes, and spatial clustering, provide completely different environmental set-ups, with quite different needs and possibilities for the firms to survive and prosper.

In general terms, the dynamic process results from the mutual interaction of these two factors, although they play different roles. The former factor

\[\text{12} \text{Again, we will not push further the analysis, but just point out that, in this way, the firm dynamics possibly resembles a series of punctuated equilibria, with long phases of relative stability (along a path of steady growth), punctuated by sudden jumps, forcing a qualitative change of structure. Moreover, it has been shown that, in the neighbourhoods of the discontinuity, bifurcations can well make structural change depending on small accidents. These small accidents can force the firm along one dynamic path irreversibly (Arthur 1989, Fuller and Moran 2001).} \]
determines the actual degree of the firm–system response to the signals coming from the environment. This allows the firm–system structure to remain qualitatively unchanged unless the signals overcome a certain threshold, thus spurring a structural change which results in the emergence of a novel system structure. The latter factor, instead, informs about the way the threshold level of the system itself changes subject to the dynamics of its environment.

The firm behaviour is thus the result of the interrelations of its two regulating mechanisms, according to which it defines a fine–tuning process of its degree of entropy. On the one side, inner mechanisms of organisational learning define a set of threshold levels for the firm capabilities, within which the firm performances are reputed to be satisfactory with respect to its goals. Indeed, this is actually what happens when the firm is capable to accommodate the environmental turbulence (mainly, but not only, of technological nature) by resorting to specific problem–solving algorithms.

On the other side, a co–evolution process is set into motion in which the firm interacts with its environment, in order to reach a dynamic balance between turbulence and entropy. Again, this is what actually happens when the firm implements different kinds of integration strategies, or sets up some kinds of institutional networks (both formally and informally) with the other actors which make up its environment and provokes its turbulence.

The complex adaptive kind of dynamics described above can be found at work also in the production–based view of the firm we describe. Indeed, the homeostatic mechanism allows firms to fine–tune their PDP by recursively exploring the dynamic mapping of the relevant sub–sets of the GW. This stage involves a process of local search within the relevant sub–space that each time is identified as the reverse salient of the PDP. According to the homeostatic principle the problem–solving activity engenders a sort of multi–dimensional local search process aimed at smoothing every bottleneck that is eventually making the process to underperform with respect to agents’ aims.

In this case, a process of entropy exchange is set in motion, when a converging routine does not yield significant results in exploring the sub–sets of the GW, to find out a convergence in processing the information necessary for an efficient PDP. In such cases the exploration activity does not find useful patterns, and in order to map usefully the various sub–spaces of the GW, it needs to reshuffle it, to see if a new significant pattern–seeking activity can be applied. In so doing, information is exchanged with the environment, and the degree of entropy of the production process (i.e. of the firm) is altered and new set of information are kept within the boundaries while other chunks are disposed of.

Once the firm dynamics is figured out in this way, also its dynamic capabilities assume a two–fold nature. On the one side, they refer to the capacity
of the firm to fine-tuning its PDP structure in order to fit its competitive relationships with the outer environment. On the other side, dynamic capabilities also refer to the capacity of the firm to (strategically) shift its boundaries, typically but not exclusively through the integration/disintegration channel, in order not to be overwhelmed when the environmental pressure becomes excessive.

5.2 The firm’s dynamics

In order to represent the firm’s dynamics, we have to start from the two polar cases previously defined. Once they are defined, we will define the firm as an entity flying on the edge of chaos, between a state of perennial change where nothing is never decided and is subject to chance, and one of freezing equilibrium, where discovery is ultimately impossible and is, again, although in a radically different way, subject to chance.

In a semantically transparent state (STS), the mapping among the four sub-sets is, almost, linear. A solution has been found which is satisfactory for the firm. The firm is actually producing everything internally, as the solution for its production process exists and is feasible: not even a single bit of knowledge is required that is produced outside, as it can be always internalised by a certain function of the GW. The external environment is either stable or is moving at a steady and predictable rate, and this makes it easy to deal with it for the firm. The solution for the PDP exists, is unique, and is stable. The environment cannot force any change whatsoever as it happens that it is ‘small’ in relation to the firm. Indeed, in such a case, vertical integration of production calls for large firms relative to the environment. Hence, the homeostatic mechanism is able to cope with relatively small environmental shocks.

The opposite holds true for a combinatorial system (CS). This is a state of perpetual flux, where no bits of knowledge is ever worth exploring, as it becomes rapidly obsolete. The firm in this case has to rely on external suppliers, as it cannot accumulate new knowledge at the rate required by the exploration of the GW. The matching among the sub-sets is made difficult by both, the number of likely patterns available, and the shifting of the various sub-sets. Indeed, each sub-set is here characterised by changing shapes of the sub-spaces, and this has implications on the way in which the pattern seeking activity looks for equilibrium solutions. The external environment is in this case ‘properly dimensioned’ with respect to the firm, and being much bigger that it, it imposes its turbulence upon the exploratory activity within the GW, in particular because the homeostatic mechanism is now rather small to cope with rather large environmental shocks. The firm is in this case perfectly disintegrated (a sort of pure assembler), as it can deal with only one source of
internally generated knowledge.

As should now be clear, these two polar cases are quite difficult to maintain for long time spans, as they miss one of the two equilibrating mechanisms described before. Indeed, they are ideal cases, interesting to define the conceptual domain of the real ones. The former case describes a firm with a large homeostatic level (larger than the environmental shocks, anyway), but with little (or no) capacity to export entropy to the environment, which is smaller that the internal firms’s environment. The latter, depicts the opposite case, as we have firms with a huge capacity to export entropy, but a rather small homeostatic mechanism (small with respect to the outer environment). Therefore, unless the firm happens to be located exactly in one of the two corner solutions (either freezed or chaotic), there will be some endogenous elements that will force the firm to change its dynamics. The process that is put in motion is therefore forcing the emergence of the ‘island’ firm. Indeed, from this point of view the firm is an emergent property of the human pattern seeking activity, that is subject to a push-and-pull mechanism between the search for an equilibrium path able to compensate the growth rate of the internal entropy by two means: on the one side, of a properly designed homeostatic mechanism calibrated on the turbulence of the outer environment; on the other side, of a relative balance in the dimension of the internal vs the external environment. Both elements are subject to so many variables, that they cannot be ‘planned’ in advance, but they are rather the result of this non–linear dynamics, a proper emergent property.

The firm environment is therefore determined by a set of external elements (sectoral, technological, etc), and depending on it, the firm finds itself with a certain relative dimension of the outer environment. This outer environment determines the firm’s ability to export entropy, and therefore the fully vertical integrated firm of the STS example, has a very limited capacity to export entropy to the environment (in the extreme case it cannot export entropy). This will determine an increasing level of disorder within the search spaces, and therefore the four sub–sets will start becoming less and less easily accommodated for in an equilibrium outcome. This difficulty will likely calls for some elements to come from outside the firm: a process of disintegration has thus started. As the process continues (the firm is not in equilibrium, hence the process cannot stop), disintegration increases. But with disintegration, the homeostatic elements become weaker and can control decreasing portions of the internal knowledge environment. Hence the firm can export entropy, but has less and less control over the environment. As the process goes on, we tend towards the other polar case, but we will never reach it, as also from this corner, firms are not able to cope with the external shocks, and in order to do this they integrate to increase the value of their homeostatic mechanism.
The actual equilibrium path will lie in between and it will not be a globally stable one, as new shocks will force the firm to start again the search process. Firms will thus emerge on the edge of chaos between the two states of pure chaos and pure freeze. In concluding, some elements are worth briefly stressing about the edge of chaos production–based view of the firm:

- The edge of chaos is the result of the behaviour and the feedback of heterogeneous agents.
- The edge of chaos is a dynamical state, and thus firms are not static entities.
- The edge of chaos cannot be planned, but it is a rather emergent property of the dynamical system.
- The edge of chaos is a particular phase in which the agents’ exploratory activity is maximum, hence knowledge exploration and exploitation is maximum on the edge of chaos, hence innovation is maximum.
- The edge of chaos is a phase in which the agents’ exploratory activity is maximum, hence in this phase the networking activity of firms is also at its maximum.

6 Conclusions

In investigating the existence, boundaries, organization and dynamics of the firm, this paper explores the complexity and potentially explosive nature of the product development process, viewed as a fundamental component of the global workspace for producers, which in turn is the set of activities unfolding from the initial (good as vector of attributes) to the final state (real commodity with given characteristics).

The analysis of the product development process emerges as a self-organising process unfolding within the global working space, which in turn is composed of subspaces.

Basic elements of our framework are the concepts of human beings as adaptive agents with goal-oriented capabilities and of organizations as complex adaptive systems, which are composed of networks of goal-seeking entities. Therefore the evolving network topology is the result of information exchanges among modules in searching for solutions to techno-productive problems. This occurs through continuous mappings between multiple search spaces, inasmuch as exploratory activities are developed by goal-oriented entities and agents in
finding appropriate values for parameters, which must belong to different vector spaces.

There are two starting points in our analysis; i.e. two prototypes: the ordered platonic world and the combinatorial system. Compositionality and recursiveness are general principles, which help us to explain how stability and variability, simplicity and complexity, orderly and chaotic behaviour can occur as emergent and essential properties during the unrolling of a variable mix of exploring and exploitation of knowledge and competences.

The proposed line of research, centred on firms as complex adaptive systems, allows us to tackle questions related to the existence, boundaries, organization, and dynamics from a different point of view. Indeed firms are conceived as flying entities on the edge of chaos in exploring the vast world between the platonic world and the combinatorial space. In this perspective dynamic capabilities are the evolutionary outcome of the actions of two equilibrating mechanisms: 1) a threshold level within the organisation learning, 2) a dynamic balance between turbulence and entropy, within the co-evolution of firms and environment.

References


Leoncini, Lombardi, Montresor


FROM TECHNO-SCIENTIFIC GRAMMAR TO ORGANIZATIONAL SYNTAX


