The Knowledge Base of Products: Implications for Organizational Structures

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Abstract

This paper investigates the impact of two dimensions of product knowledge bases on organizational structures. The first dimension, knowledge breadth, measures the complexity of a product. The second dimension, knowledge depth, measures the extent to which the knowledge embedded in the product can be used in different contexts. An agent-based simulation study is carried out to analyse the structural characteristics of organizations that emerge when self-interested agents select partners to combine their expertise and produce together. Agents learn from their interactions, which shapes their choice of partners in the future. The results reveal that multi-product companies with fewer inter-firm relationships emerge when products are complex and knowledge is highly reusable in different contexts. A network of specialized firms is a dominant organizational structure when products are complex and deep. The results are demonstrated through a brief case study of the history of the computer industry.

Keywords: networks, knowledge, firm formation, simulation

Introduction

Since the seminal work of Ronald Coase (1937), the central questions addressed by theories of the firm have been why firms exist and what determines their boundaries. It was transaction cost economics (TCE) that initially addressed these questions in modern economic theory (Williamson 1985).

More recently, research on the formation of organizations has moved beyond the investigation of the boundaries between firms and markets, by incorporating other governance types into their framework. One of these is the inter-firm network, which has been a widespread organizational form in many industries since the mid-1980s.

TCE has been criticized for failing to provide a robust explanation for inter-firm networks with respect to its behavioral assumptions, like opportunism, and its inability to consider the effects of rapid technological change and instability (Conner and Prahalad 1996; Ghoshal and Moran 1996). More recently, a range of other approaches have deepened our understanding of the existence and boundaries of organizations, such as the resource-based and knowledge-based theories of the firm (Grant 1996; Kogut and Zander 1992; Nonaka 1994; Wernerfelt 1984).

This paper addresses the role of knowledge requirements of production in the shaping of an organizational context. The main premise of the paper is that the

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knowledge base of artifacts shapes the process of knowledge exchange between producers. Production is taken as a jointly performed activity, in which different actors contribute their expertise. Two dimensions of the knowledge base are defined as knowledge breadth and knowledge depth, which refer to complexity and economies of scope, respectively. In the agent-based simulation model, self-interested actors select partners, combine their knowledge for the purpose of production, and their knowledge levels increase during these interactions. A mapping is made between the breadth and depth dimensions of the knowledge base and the organizational structures that emerge from these interactions. If one defines innovation as a recombination activity in which a particular knowledge type is applied to a new context, then innovation can be seen as a change in one or both dimensions of the knowledge base of products. In this sense, this study also sheds light on how different types of innovation shape organizational structure.

The paper is organized as follows. In the second section the theoretical background is presented. This part draws upon the literature on product modularity and its implications for organizational structure, knowledge-based theories of the firm, and inter-firm networks. The third section presents the rationale of the model, the research questions addressed and the algorithm used to run the simulations. The fourth section is devoted to simulation results and their interpretation, as well as to a brief case study on the evolution of the computer industry. The final section contains some concluding remarks.

Background: Product Architecture, Knowledge and Organizational Structure

Product Modularity

In the framework of industrial production systems, the concept of modularity is mostly applicable to assembled products. The origins of its formalization date back to Herbert Simon's (1962) analysis of managing complex systems by breaking them down into modules. Schilling (2000: 312) defines modularity as 'a continuum describing the degree to which a system's components can be separated and recombined'. Baldwin and Clark (2000) define it as the ability of the system to be split into smaller parts with weak integration points between them.

As far as the impact of modularity on organizational structure is concerned, one point of view emphasizes that modularity results in loose coupling between organizations (Langlois and Robertson 1992; Sanchez and Mahoney 1996). In highly integrated systems, a change in one component requires significant changes in others. In modular systems, the weakening of dependences facilitates the separation of tasks, whereby different teams can specialize in the production of each module. In complex product systems, depending on assemblers' strategy of interaction with suppliers, such specialization may intensify interactions between firms (Pavitt 2005).

Focusing exclusively on the complexity of product architecture may undermine the many-to-many relationship between knowledge and products, and its implications for organizational structure. The modularity of a product system conveys little information about which competences are required to produce each module. It is important to understand underlying competences because the additional knowledge that is acquired during production is not only confined to its current use, but can also be used in different contexts, either within the same product system, or to meet different needs altogether. In this sense, the organizational context responds not only to the physical architecture of the product system, but also to the knowledge base of this architecture. One of the consequences of undermining the knowledge-base of product systems can be an incomplete analysis of the boundaries between markets and hierarchies. The modularity of a product system may facilitate division of labour beyond or within the boundaries of a firm, but it falls short of explaining where the firm ends, and where networks begin.

In the computer industry, many innovative small firms were formed during the 1980s, with intensive networks among them. Such an organizational landscape was not only the result of the modular design of computers. The reusability of the knowledge to meet different needs also played an important role (Steinmuller 2007; Langlois 1999).

In addition to economies of scope, the range of different competences required in production also shapes the organizational structure, by intensifying inter-firm networks, and by driving firms to technological diversification. These two dimensions of product knowledge bases and their implications for organizational structure have been studied before, albeit in disparate strands of literature. The next section provides a brief review of this literature.

The Knowledge-based Approach

Focusing exclusively on the physical architecture of products undermines the implications of the complex relationship between knowledge and products. This relationship is not one-to-one; just as a certain competence can be used to produce a variety of products, so can a single product draw upon a variety of competences, making the mapping many-to-many (Pavitt 1998). In the literature, each side of this bidirectional relationship and its implications for organizations has been addressed in separate theoretical frameworks and they complement each other. Firstly, the one-to-many relationship is explained below, which addresses the implications of reusability of a piece of knowledge in different products. Secondly, the many-to-one relationship is analysed, which refers to many competences making up a single product.

Economies of Scope arising from Reusability of Knowledge

It was Edith Penrose (1959) who first formalized how an organizational structure is shaped by economies of scope, a line of research further developed by Teece (1980). Because human capital can be used to produce a variety of related products, firms that have excess resources can lower marginal costs by diversifying into related product categories. Teece (1980) uses this framework to explain related diversification and the emergence of multi-product firms.

During the 1980s the field of economics of innovation and technology has improved our understanding of the nature of knowledge as an input in production

(Nelson and Winter 1982). Two important features of knowledge are that it is inexpensively reproduced (expansible), and that its use by one party does not exclude others from using it (non-rivalrous). These aspects of knowledge influence the sources of economies of scale and scope in the industry. For example, according to Steinmuller (2007), one of their impacts on the ICT sector is the ability to reuse an original design to satisfy different needs. In this case, he explains that the 'first mover' advantage in innovation may not last for long, since rapid technological change may increase the opportunities for rival firms to make new and improved designs. In other words, economies of scope in ICTs stem from the ability to 'address different application needs with the same designs' (Steinmuller 2007: 198). This creates important opportunities for product differentiation. Consequently, in the software industry, many specialized firms producing complementary products were formed.

The second way in which products and knowledge are related to each other is when a single product draws upon a variety of competences. According to the literature, two of the organizational impacts of complexity are the increased interactions beyond firms' boundaries, and the emergence of multi-technology firms.

Inter-firm Networks

The earliest approach explaining why firms form collaborations is the resource-based approach. The resource-based view (Wernerfelt 1984) emphasizes the role of complementarities in resources. Firms form alliances with others because they are not self-sufficient, and they collaborate to reduce uncertainty and to access each others' resources (Pfeffer and Salancik 1978), especially in technologically intensive industries (Hagedoorn 1993).

Based on empirical evidence in various industries, one of the motivations behind R & D alliances is the increasing complexity of products and rapid technological change (Hagedoorn 1993; Contractor and Lorange 1988). According to Hagedoorn (1993), in sectors where interrelatedness and complexity are high, technological complementarities are a significant motive to create alliances. Other motivations include access to markets and a reduction in the innovation period, which are more valid incentives in relatively mature industries. In biotechnology, the complexity and multidisciplinary character of the knowledge base has been a significant motive, which draws firms into external collaboration (Hagedoorn 1993; Orsenigo et al. 1998). The knowledge base is widely dispersed and collaborations are between large and established pharmaceutical firms who offer market access opportunities, and small firms who make a scientific and technical contribution (Arora and Gambardella 1990; Walker et al. 1997). Research has shown that one of the most important processes that accompany alliances is organizational learning (Powell et al. 1996; Hagedoorn and Duysters 2002; Oliver 2001).

Multi-technology Firms

According to the literature, another organizational impact of product complexity has been the technological diversification *within* the firm. Research has shown that most large firms extend their technological competences to a range of technologies broader than those required by their core product lines

(Grandstrand and Sjolander 1990; Grandstrand et al. 1997; Patel and Pavitt 1997; Brusoni et al. 2001). For example, Torrisi and Gambardella (1998) find that increased product focus is accompanied by increased technological diversity in the electronics sector, yielding higher performance. One of the motives behind technological diversification is to improve the absorptive capability of the organization and to make better use of technological opportunities in this way.

Summary

Figure 1 summarizes the theoretical background of this paper. The rows in the table correspond to the two dimensions of knowledge base, and the columns correspond to how an organizational structure is shaped at the firm and industry levels, according to the existing literature.

Knowledge-based theories of the firm state that economies of scope result in related diversification at the firm level (Teece 1980). At the industry level, economies of scope might yield an organizational landscape with many specialized firms, producing a rich array of complementary products, as in the computer industry. When product systems are increasingly complex, firms may diversify into a wide range of technology fields, to be able to monitor novelties and increase their absorptive capacity. An industry-level response to increased complexity has been the rise of the inter-firm network as a hybrid organizational structure between firms and markets (Powell 1990).

There are a few issues lacking in the foregoing analysis. Firstly, while disparate strands of research investigate the effects of complexity and economies of scope on organizational structures, a systematic analysis of their joint effects is lacking. Consequently, the existing literature does not provide a complete picture of where firms end and where networks begin, with respect to the two dimensions of the knowledge base.

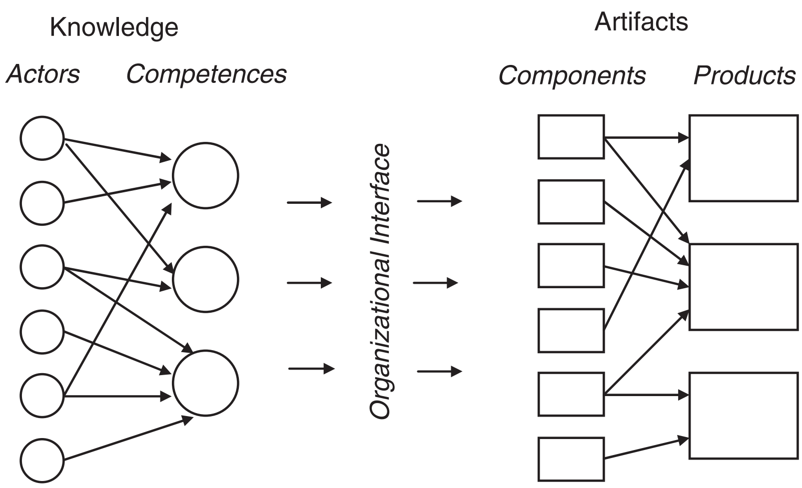
The Model

The model investigates how the many-to-many relationship between knowledge and products shape organizational structures. In this section, the main logic of the model is explained and the algorithm of the simulations is given.

Figure 1. Knowledge and Organizations: Existing Literature

	Level of Analysis	
	Firm-level	***Industry-level***
From knowledge to products		
One-to-many: Economies of scope	Related diversification *(Teece 1980)*	Complementary products, specialized firms *(Steinmuller 2007)*
Many-to-one: Complexity	Technological diversification, division of labour *(Grandstrand and Sjolander 1990)*	Inter - firm networks *(Powell 1990)*

Figure 2.
The Two Conceptual Categories of a Production System



In Figure 2, the production system is split into two conceptual categories. The first category refers to knowledge that is stored and diffused by human beings. The second category refers to artifacts, which are composed of components and products. Knowledge is used as an input in the production of artifacts. The conversion of knowledge into artifacts happens within an organizational context. In other words, organizations are interfaces connecting people and the artifacts they produce. The organizational context is shaped by interactions between people who use their competences to produce goods and services. One of the important forces that shape these interactions is the knowledge requirements of production. In other words, interactions depend on how competences are mapped onto products. In this paper, we investigate the organizational implications of different ways in which this mapping occurs.

The real world is obviously more complicated than illustrated in Figure 2. For one thing, productive actors are highly heterogeneous with respect to their competences. In addition, as discussed above, there are many different ways in which competences can make up products. Moreover, each product has a unique configuration in terms of the type and intensity of the competences it requires. Furthermore, as people interact within an organizational context, their knowledge endowments are continuously changing, which further shapes their interactions and production activities in the future. Some of the factors that influence this learning process are the tacitness of the knowledge base, technological opportunities and the idiosyncratic learning capabilities of people. Finally, as people learn, the way knowledge is embodied in products is also changing, as new products are designed.

Despite these complexities, it is possible to observe at least two patterns in the knowledge bases of different industries in the real-world. One of these patterns is concerned with the array of different competences required for production. Some products draw upon a wider knowledge base than others. The difference between restaurants and automobiles illustrates this point clearly. In the former, the competences required to create the final product/service include choosing the ingredients, preparing the ingredients for cooking, the cooking process, preparing for service, and the delivery of the service to the end-user. All these activities draw upon the tacit knowledge of the ‘chef’. Because these activities are highly related, the knowledge underlying them can be stored and used by a limited number of people. That is to say, a person who 'knows' how to select the best ingredients will in general know how to prepare them for cooking, how to cook them and how to prepare the final dish. In the case of automobiles this process is more complex. There are too many distinct competences required to produce an automobile, such as electronics, painting, mechanics and assembly. It is not possible for a single actor to be endowed with all these competences, and inevitably tasks are shared between productive actors. These issues are very clearly explained by Baldwin and Clark (2000: 5):

> 'If we think of arraying artifacts along this [complexity] spectrum, two interesting points arise as we move from simple to complex. 1. The point at which an artifact can no longer be made by a single person; and 2. the point at which an artifact can no longer be comprehended by a single person. Crossing into the first requires division of labour. Crossing into the second requires a division of the knowledge and effort that go into creating the design.'

So, sharing the tasks in a restaurant is an example of division of labour. In general, one expects that the chef comprehends all the tasks in the production process, but he or she might be limited in his or her physical capacity to satisfy the needs of too many customers. The case of automobiles includes both dimensions: it is beyond the physical capacity of a single person to produce a car, and also it is beyond his or her capacity to know all the components and the interactions between them. In this case, the knowledge-integrating firms have a central role in coordinating specialized tasks in a modular network (Brusoni 2005).

The second pattern that is observable in the knowledge bases of industries is the economies of scope that arise from the reusability of competences to meet different user needs. For example, a computer programmer can apply his or her knowledge to meet a range of different user needs. Thus, in some industries, there are greater opportunities for product differentiation.

The model presented below incorporates this complex picture of competences, products and organizational structure within an agent-based simulation model. In social sciences, the last 20 years have witnessed a surge of interest in agent-based simulation models, with the understanding that any attempt to explain aggregate patterns has to take into account the particular interaction structure among heterogeneous agents and how this structure evolves. One of the aims of utilizing agent-based simulation models is to explain emergent global behaviour, and to answer the question, 'Why have particular global regularities evolved and persisted in real-world decentralized market economies, despite the absence of top-down planning and control?' (Tesfatsion 2003). The approach in this paper is similar, in that organizational structure is taken to be an emergent property resulting from the interactions between people.

Modelling the Knowledge Base Regime

In the model below, two dimensions of the knowledge base of an industry are considered. The first dimension is inspired by complex products and measures the range of different competences that products embody. This dimension is termed the *knowledge breadth* of artifacts. The second dimension of the knowledge base is inspired by the concept of economies of scope and measures the extent to which a certain competence can be used to produce a range of different products. This dimension is termed the *knowledge depth* of artifacts.

One way to represent this two-dimensional conceptualization of products is to construct a hypothetical matrix that shows the relationship between products and their knowledge requirements. As an example, Figure 3 illustrates four distinct knowledge base regimes for three products (*P1, P2 and P3*) and three knowledge types (*K1, K2 and K3*). In the matrices, a_{ij} gives the weight of competence *j* required in product *i*.

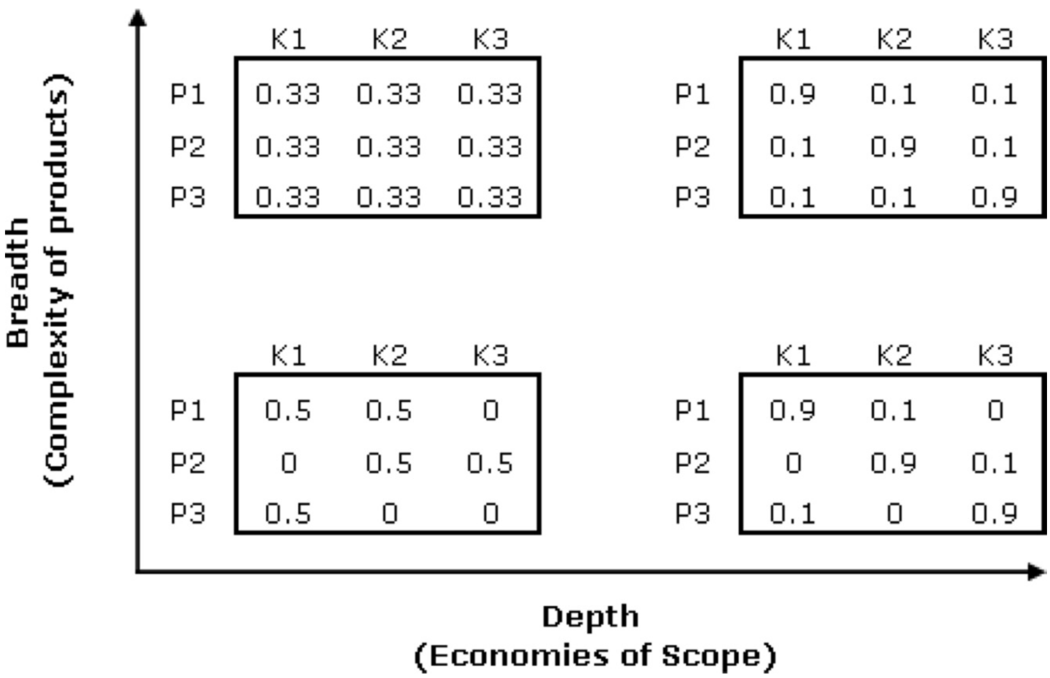
In Figure 3, the vertical axis represents the knowledge breadth of products. In the upper two matrices, all three types of knowledge are used in all three products. The horizontal axis measures the economies of scope. If a certain knowledge type can be used with equal weight in different products, then the knowledge depth is considered to be low. This is represented by the matrices on the left-hand side. The depth of the knowledge base increases as competences become more product-specific, which makes them difficult to be employed in the production of other goods and services. For example, the lower right matrix shows basic products with limited economies of scope. Knowledge type *K1* is highly specific to *P1*, and has a low weight in the production of *P3.*

These matrices are shown for illustrative purposes. An example set of matrices used in one of the simulations is given in the Technical Appendix.

A Schematic Description of the Model[1]

There is a population of actors who are endowed with different types of competences. These competences can be utilized to produce a variety of products. The way these competences are embodied in products is a parameter taken exogenously, so as to capture differences in the knowledge base regime, as explained in the previous section. The quantity of products that an actor can make depends

Figure 3. Four Examples of a Knowledge Base Regime



on how knowledgeable he or she is in the relevant fields, and also on the weight of the different fields required by each product.

Actors can produce by themselves, or alternatively they can select partners to produce jointly and share output. The formation of a partnership between two agents depends on mutual consent. Therefore, a partnership is formed only if both sides find it beneficial to do so. The benefits depend on knowledge complementarities between two agents. Agents learn from these partnerships, depending on their learning capabilities and previous knowledge levels. As their competences change, so do their partner preferences in future periods. The simulation study consists of a large number of periods, and the foregoing steps take place in each period. After sufficient periods elapse, one obtains a matrix showing which agent interacted with which one, and how many times. In other words, in one period there are only dyadic relationships but, as sufficient periods elapse, these linkages cumulate so as to yield a network of agents. By utilizing social network analysis techniques, these networks are partitioned into groups. The structures of these groups are analysed by using the final knowledge endowments of the actors who form them. The simulation run described is repeated for a variety of knowledge breadth and knowledge depth combinations. The average values obtained from 20 repetitions of this process are given under 'Results' below. The algorithm of the model is given in Figure 4.

Results

The intensity of connections in a network can be measured by the density of the network. It is calculated in the following way:

$$D = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} x_{ij}}{N(N-1)}$$

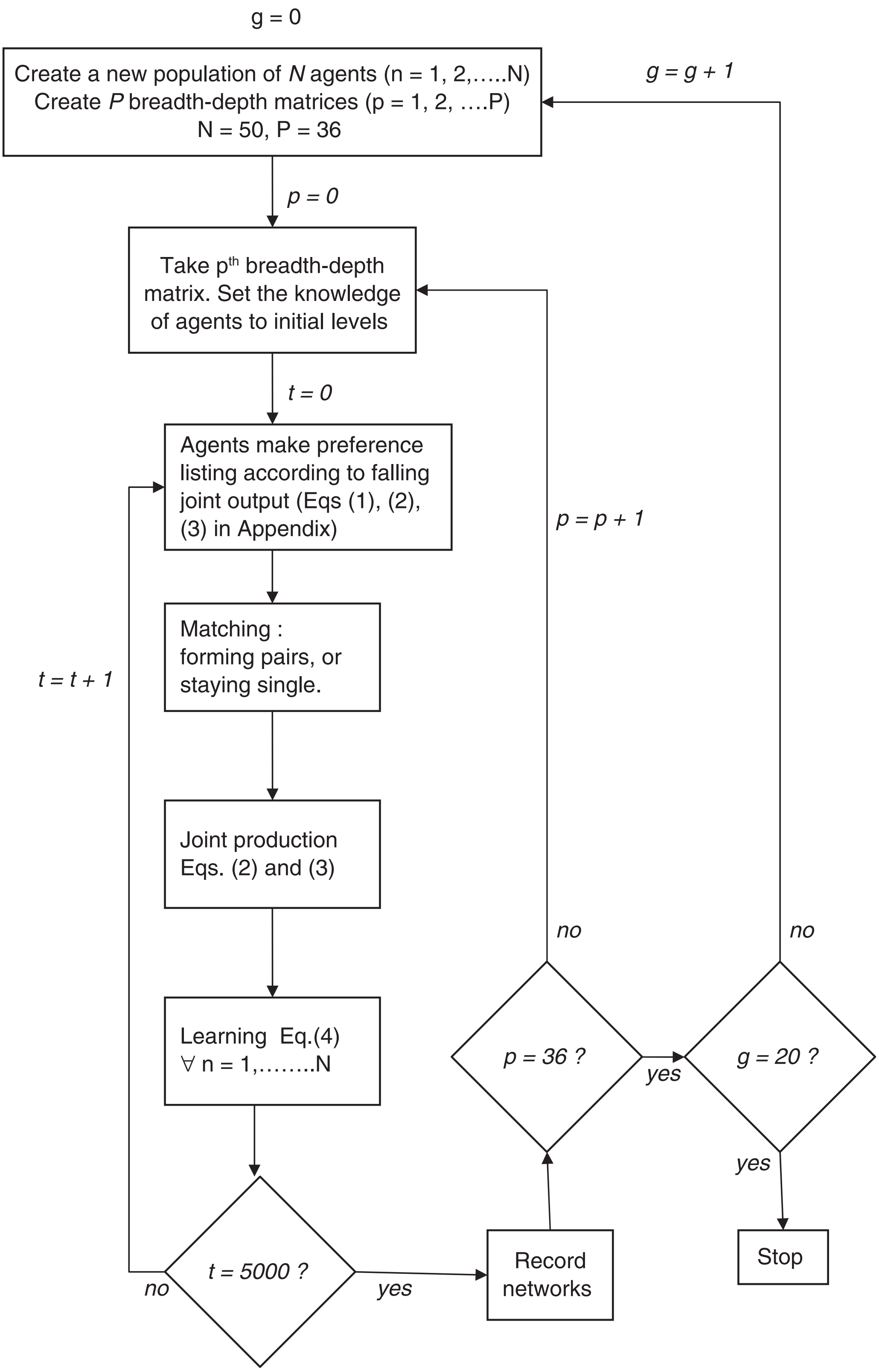
where $x_{ij} = 1$ if there is a link between i and j and is 0 otherwise, N being the total number of nodes. As evidenced in Figure 5, the average density in final networks is highest in the upper right corner. In this area, the knowledge base is broad and deep. In other words, products utilize many knowledge types, and one of them more intensively than the others. The two regions in which network density is lowest are the upper left corner and the area in which the breadth of the knowledge base is lowest (the lower region in Figure 5). In the remaining regions, network density is moderate.

The final networks are partitioned into groups using clique analysis.[2] A clique is defined as a subset of agents all of which have links with each other and there are no other agents in the network that have links to all of the members of the clique (Luce and Perry 1949).

Product Diversification, Technological Diversification, and Inter-group Relations

This section presents the analysis carried out concerning the structure of cliques. Structural analysis is based on three measures in line with the theoretical framework

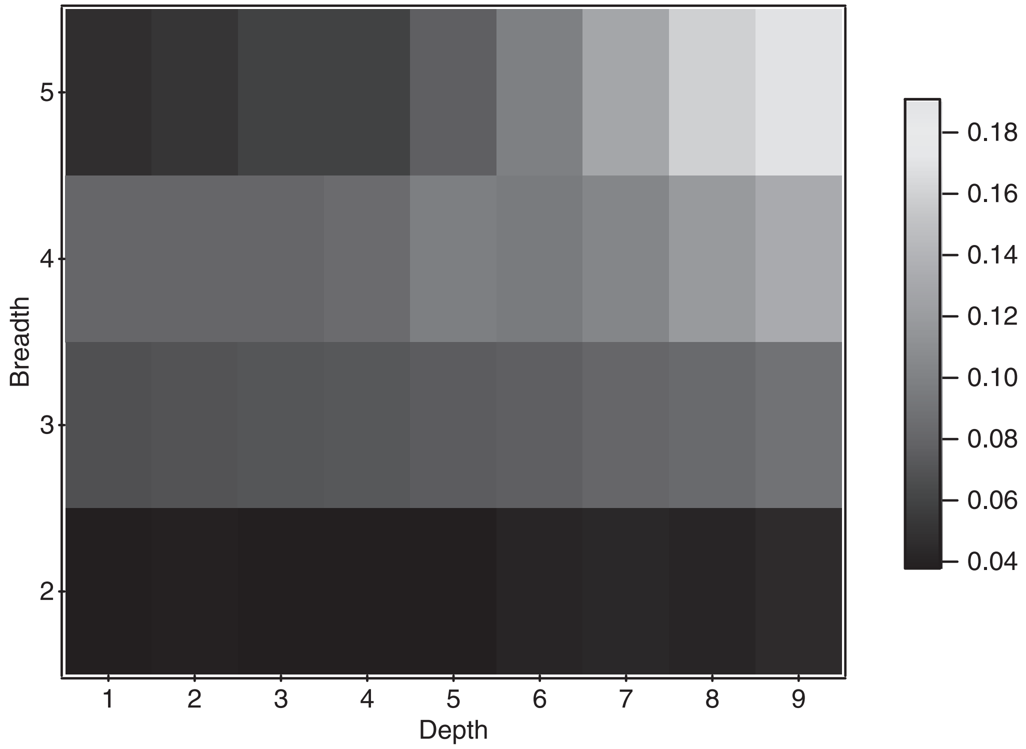
Figure 4.
Algorithm of the Model



presented in Figure 1: product diversification, technological diversification and inter-group relations.

In the breadth and depth space, product diversity in the cliques is given in Figure 6. Each clique consists of a number of agents, each of which produces

Figure 5.
Network Density



one type of product. Product diversity is measured by the number of different types of goods produced in a clique, weighted by the number of clique members producing it and the average taken over all cliques in a single run. Figure 6 shows that, for each level of breadth, depth has a negative effect on product diversity. In other words, the more the knowledge can be reused in different products, the more diversified the groups become. This effect gets more pronounced as products get more and more complex (as breadth increases).

Figure 7 gives expertise levels in cliques, used as a proxy for the opposite of technological diversification. Expertise is measured by the standard deviation between different knowledge types in a clique. According to Figure 7, the cliques in the upper right corner and those in low-breadth areas are experts in certain knowledge types.

Finally, clique overlap is shown in Figure 8. Overlap is used to measure the extent to which there are inter-clique interactions. The inter-clique relations are densest in the upper right corner, where products have high breadth and low depth.

These results point to the emergence of four distinct regions in terms of organizational structures. These regions are summarized in Figure 9 and interpreted in the following section.

Regions I and II: Narrow Knowledge Base

In the first region, products draw upon few competences. This implies that complementary competences are not vital for production. Consequently, agents prefer to produce either alone, or form partnerships with those that have the same type of competences as themselves. Once a partnership is formed, it lasts for a long time. Since partnerships are formed between agents producing the same

Figure 6.
Product Diversity

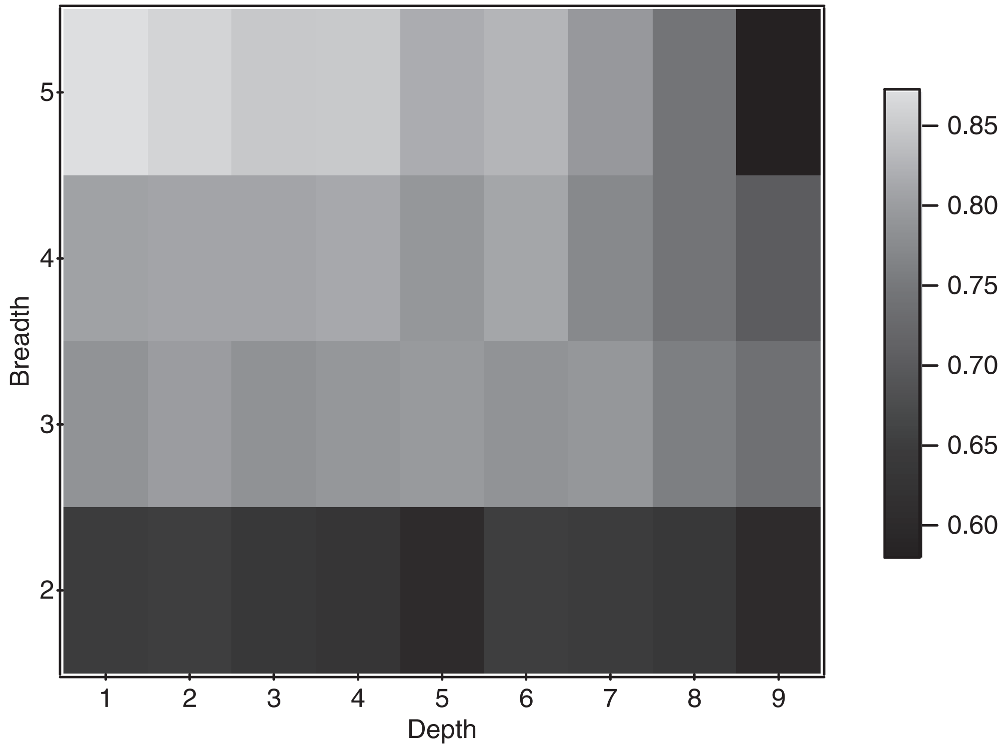
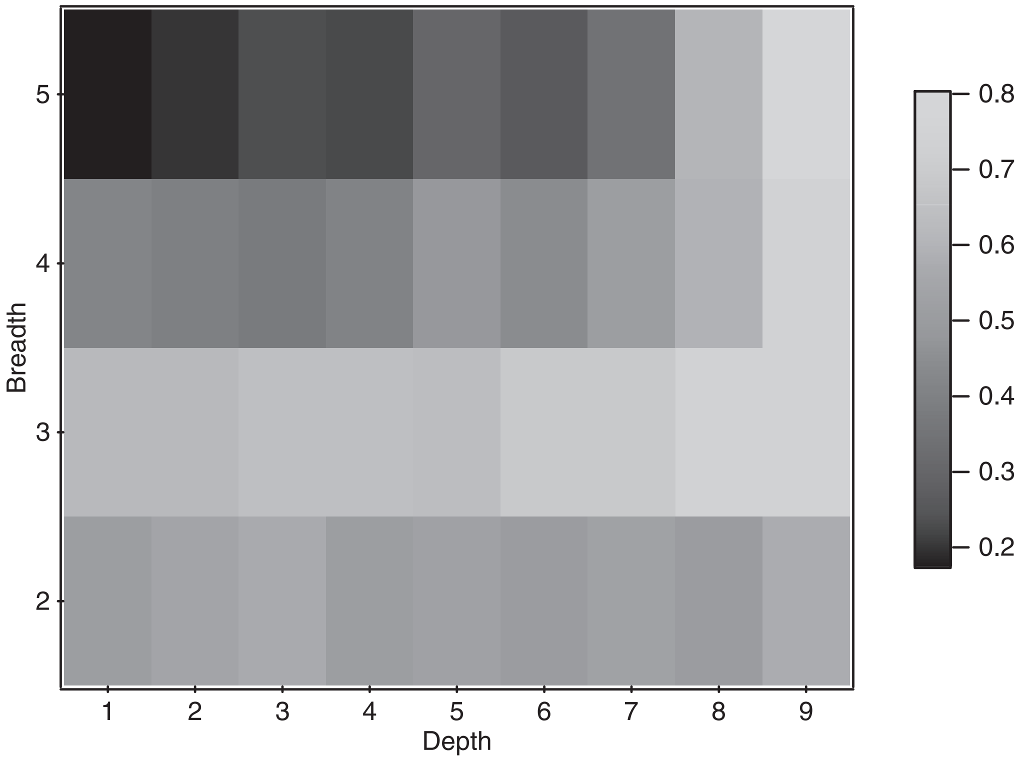


Figure 7.
Expertise



products, product diversity in cliques is low (Figure 6). If goods draw upon a narrow knowledge base, and if the same types of agents form pairs, then agents learn only in the knowledge types utilized, and no learning takes place in other competences. This increases specialization (Figure 7). A high level of specialization reduces the incentives to interact with a diverse set of other agents in the

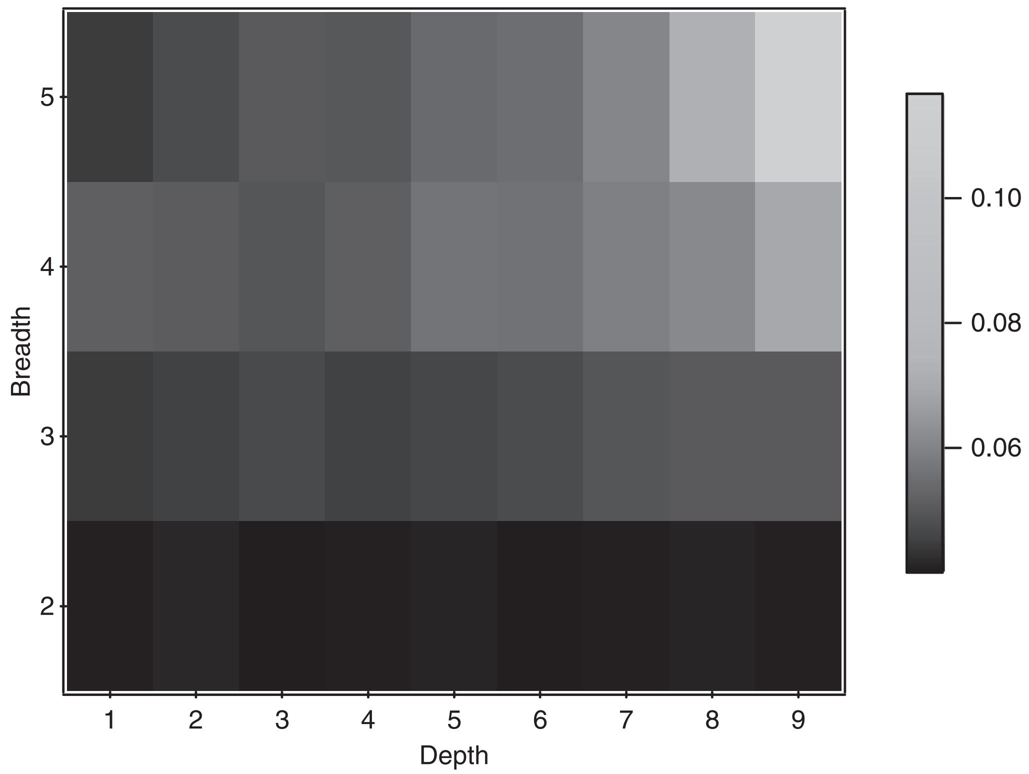


Figure 8.
Clique Overlap

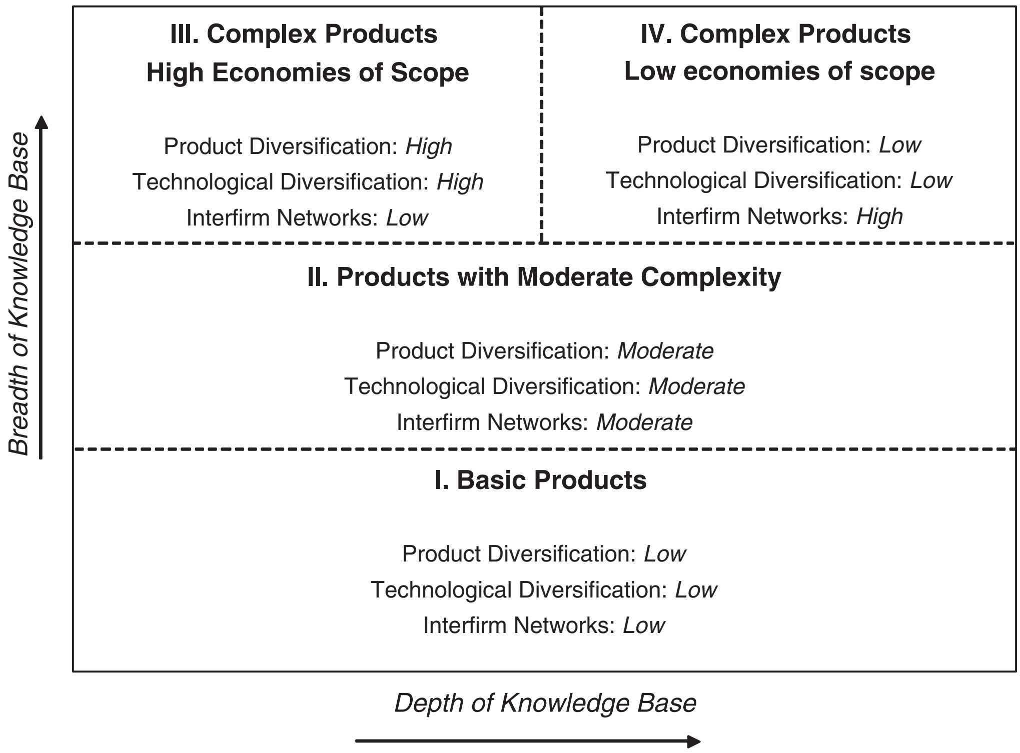


Figure 9.
Organizational Structures in the Breadth and Depth Space

future, since there can be little knowledge in common. In this region, clique overlap is low (Figure 8), which points to few interactions among groups.

Restaurants, hairdressers, local specialty shops and real estate agencies are some examples that can be characterized by a narrow knowledge base, and where competences are highly product-specific. In these types of products and/or services, organizations are to a large extent specialized and they have little interaction with one another. To take the example of restaurants, most of the competences required for the preparation of the final service can be embedded in one actor, who is the 'chef'. Moreover, his or her competence is rather difficult to apply in other contexts. Consequently, he or she is not expected to be highly motivated to form partnerships with other chefs. The same kind of argument is valid for services like hairdressers or real estate agencies. In those industries one observes highly specialized firms working independently of each other, and where relationships with other firms are mostly competitive rather than cooperative. Knowledge used is highly specific to products, and the resulting organizational landscape is characterized by the dominance of specialized and disconnected firms.

Region II is largely transitory, after which economies of scope begin to show its effect on organizational structure as breadth increases further. The patterns observed in regions III and IV can also be seen here, albeit less vividly.

Regions III and IV: Complex Products

As products become more complex, the resulting organizational structure changes markedly. When the knowledge base is at its broadest, two distinct regions emerge, III and IV, corresponding to shallow and deep knowledge bases, respectively.

In region III, knowledge is equally reusable in different products. Within a population of largely isolated cliques (Figure 8), each clique has high product diversity (Figure 6). In this region, agents making different products form pairs. This pattern differs from the narrow knowledge base in region I, where agents producing the same products form partnerships. Cliques are not specialized in a certain knowledge type; rather, various kinds of expertise coexist within them (Figure 7). In addition, inter-clique relations are not as intense as in region IV. This region strongly resembles multi-product firms, after the manner of Teece (1980).

Why is this pattern observed here? According to the model's underlying mechanism, the motivation to form a partnership depends on whether two agents can jointly produce more than they could do by themselves. Because all competences have equal weight in products, two agents producing different products are as likely to form a partnership as two agents producing the same product.

One of the examples from real-world industries is the domestic appliances sector. A variety of products serving different end-user needs are white goods, such as refrigerators, washing machines, ovens and small home appliances. Their production processes usually require a complex array of competences, including design, mechanics, electronics, painting, assembly and the like. In addition to the knowledge base, the magnitude of economies of scale and of high fixed costs also contribute to the emergence of firms that are multi-product, as in the case of giant home appliance producers.

Region IV is characterized by complex products and weak economies of scope. Final products embody a wide range of different competences. But there are limited chances for using competences in different products. In other words, competences are largely product-specific, but not totally so. It is possible to use a certain competence in a different context, albeit with reduced productivity.

In this region, the cliques are specialized both in terms of products and knowledge (Figures 6 and 7), with a high amount of overlap between them (Figure 8). To explain the mechanism resulting in such an organizational structure, it is relevant to analyse the nature of partnerships in region IV. According to Figure 6, which shows clique product diversity, there is a tendency for similar agents to form partnerships. Nevertheless, because products draw upon a variety of competences, even a slight change in the choice of partners results in learning in other areas. Because of this rapid change in agents' competences, partnerships are not necessarily long term as in the case of Region I. As agents change partners, they learn in different areas, which further induces them to change partners. Only in this region specialization is accompanied by intensive networking (Figures 7 and 8).

The region strongly resembles industries characterized by modular products, where firms specialize in certain products that are complementary to products made by other firms. Telecommunications, automobiles and computers are obvious examples to this kind of knowledge regime.

Evolution of the Computer Industry: A Complex Network of Artifacts, People and Organizations

The evolution of the computer industry is full of interesting examples illustrating the complex nature of networks among people, artifacts and knowledge, demonstrated by our model. The history of the computer industry begins in the 1940s.[3]

Between the 1940s and the 1970s, IBM was one of the leading organizations within which computer science and industry was being developed through intensive research and product development activities. During this period, the industry's knowledge landscape was sparse not only with respect to the level and sophistication of existing knowledge, but also with respect to the availability of skilled people capable of designing and producing computers. The dominant logic prevailing in organizations was based on a closed model in which there was little knowledge flow beyond firms' boundaries. Furthermore, a wide spectrum of knowledge could be embodied by a few star scientists working in these giant organizations. Founded in 1970, Xerox PARC is another example of such firms.

In the USA, during the 1970s and 1980s computer scientists, physicists, and talented recent graduates of leading universities formed a closely knit network, continuously sharing and creating new knowledge, especially around Silicon Valley. The community was made up of experts in knowledge fields such as neuroscience, electronics, psychology, programming, design, human computer interactions, pattern recognition, hardware manufacturing, physics and so on. These fields were continuously being deepened and were being used to develop applications, eventually leading to the production of new products or the addition of new features to existing products. In this way, either disparately or within strongly connected scientific and entrepreneurial networks, people were not only exploring the knowledge landscape, but also laying the foundations of many electronics-based products, like tablet computers, the mouse, printers, personal digital assistants (PDA), game consoles and digital cameras.

Obviously, the beginnings of the personal computer (PC) industry during the 1970s were characterized by a rich array of technological opportunities. In an abundant knowledge landscape, many of the ideas and technologies that were being used in one context could find applications in other contexts, as people with different specialties interacted and shared their knowledge. But more importantly, the way such economies of scope were being exploited was marking the beginning of an era in which new electronic products were becoming not only more *complex,* new features being added continuously,[4] but also much more *specialized*. This was making it more difficult for large firms to incorporate all kinds of competences within their boundaries. It also explains how the organizational landscape was shifting from a few dominant and largely 'closed' firms to many dynamic and innovative start-ups with intensive networking among them.

In fact, what was happening in the computer industry during the 1970s and 1980s was a transition from a narrow knowledge base with rich economies of scope, to a markedly different knowledge regime, which was more complex and more specialized. This transition was accompanied by an organizational change from the dominance of few large firms to many specialized start-ups. The development of portable computers exemplifies this transition.

During the 1970s, one of the limitations of computers was that they were too big, and few entrepreneurial scientists were working on developing computers with electronic displays small enough to be portable.[5] The 'Grid Compass' was one of these early attempts to design a portable computer, developed by a few engineers from the Xerox PARC network. The design and development of the laptop involved solving many technical problems concerned with the size of memory, modems, and screen. These problems were solved through intensive interactions among teams of engineers from various companies like Intel, who supplied the bubble memory; Racal Vadic, who designed the modem; and Sharp electronics, who designed the electroluminescent screen. The final product was the portable computer called the 'Grid Compass'. It was through these intensive interactions that each team of engineers acquired knowledge from each other. Consequently, portability was becoming a new design feature, requiring specialized knowledge on how the components, now much smaller in size, worked together.[6] Soon after, this design feature became the core competence of some firms that developed PDAs and tablet computers.[7]

Discussion and Directions for Future Research

This paper investigates the organizational impacts of two dimensions of the knowledge bases of industries. While knowledge breadth measures the complexity of products in terms of different competences they embody, knowledge depth measures the extent to which knowledge that makes up products can be reused in different contexts. In the space defined by these dimensions, what types of organizations exist? To address this question, an analysis of the structure of organizations emerging through the interactions of self interested agents is carried out. The theoretical angle of the model permits it to be applicable to a wide range of contexts, other than firms and industries, in which an organizational context is shaped through the interactions between people. Another context in which such a model could be applied is the evolution of not-for-profit organizations.

As a very rich literature reveals, the institutional context, demand side-effects and scale economies are some of the important factors which influence organizational structures. However, the way knowledge is embodied in artifacts has received relatively less attention in comparison. The existing literature on the relationship between knowledge and organizational structure was summarized in Figure 1. One of the aims of this paper is to draw attention to a few issues not yet dealt with in the literature.

Firstly, disparate fields of research analyse the effect of economies of scope and complexity on organizational context, but a systematic analysis of the joint effects of the two is difficult to obtain. In this paper, an attempt is made to fill this gap by taking into account both dimensions of knowledge.

Secondly, the literature on modular systems is concerned with complexity at the level of physical components. It advances our understanding of how the physical architecture of products reflects upon organizational structures. But focusing exclusively on the physical architecture may result in discarding the impact of knowledge embodied in products. Learning taking place during production is not only confined to the properties of the product at hand but, more than this, it includes an increase in the level of general knowledge embedded in the product. It is important to underline this because the additional knowledge can be used in other contexts than the ones in which it is originally utilized. The histories of industries are full of examples in which such economies of scope have shaped the way organizations form and evolve. The computer industry is an important one in this respect. Major actors who were initially endowed with highly scientific knowledge had an important role in creating and diffusing knowledge in their respective networks. In return, these disparate competences that were used in one context could find applications in different contexts, forming the basis of many specialized electronic products in use today. As the economies of scope were being exploited, the organizational landscape was shifting from the dominance of a few large firms to a network of many small and innovative enterprises.

The third weakness associated with the current literature is a consequence of the above two. In particular, because the two dimensions of knowledge are not taken into account jointly, one has a relatively incomplete picture of where firms end and where networks begin. This paper seeks to complete this picture by analysing which types of organizations exist in a two-dimensional knowledge landscape.

It is important to underline a few critical points when interpreting the results of the model in the real world. Firstly, the model is based on the knowledge-based theory of the firm. In this view, the main incentive to form partnerships between economic actors is to combine complementary competences that are necessary for production to take place. In this sense, the relationships are governed by complementarities in the knowledge endowments of producers, rather than being governed by an exchange of intermediary products to achieve cost efficiency. In this sense, the model does not cover the classic trade-off between making and buying based solely on cost considerations.

Secondly, this model assumes a closed world in which the number of products, knowledge and agents are fixed. But it does not exclude the process of innovation. Our knowledge about the innovation process reveals that innovation can be perceived as a recombination of disparate knowledge types. In other words, in most cases innovation occurs when a particular competence is applied to a totally new context (Hargadon 2003). In this model, this would correspond to the case where a new product is created through a change in the knowledge depth and/or breadth of one or more of the existing array of products. That is to say, innovation connotes a movement in the breadth and depth space. In this sense, the model has implications for the evolution of organizations in response to different types of innovation. One of the weaknesses of the model is that the knowledge base is taken exogenously. One of the directions that can be undertaken in future research is to *endogenize* the innovation process to reveal how networks among people co-evolve with the knowledge base of products.

Third, the model sheds light on how organizational structures are shaped without any top-down planning and control. This is not to deny the existence of authority as a mechanism that maintains coordination and control within an organization. One of the premises of this model is that authority is an ex-post mechanism which maintains coordination and control, but not a necessary condition to legitimize the existence and formation of organizations ex ante.[8]

In addition to the above, the model assumes that agents are output maximizers. One can argue about the extent to which output maximization is a reasonable strategy in organizational environments. In this paper, we contend that it is a *viable* strategy, especially in environments where actors search for complementarities between their competences. However, being an optimizer does not necessarily mean that one is able to do so in the real world. This model shows the patterns that emerge when agents cannot fully optimize even if they intend to. In fact, in most cases, they cannot optimize since their rationality is bounded, they are heterogeneous and the environment is too complex and uncertain.

Finally, in this model, modularity is not explicitly included. Modularity focuses on the interfaces between the physical components of a product, rather than their knowledge content. This model shows how such knowledge content can influence organizational settings. In this sense, the implications of this model are complementary to the literature on modularity, rather than being an attempt to challenge its results. One of the promising directions for future research could be to incorporate modular systems in a framework similar to this model.

The results of the model can be summarized as follows. First and foremost, the more complex the knowledge bases of products, the greater the effect of economies of scope on organizational structures. In the case of complex products, diversified organizations exist when economies of scope are rich. This is an established result in firm theories, mainly after the pioneering work of Teece (1980), who explained the existence of a multi-product firm with respect to economies of scope. On the other hand, complex products and weak reusability of knowledge result in specialized firms with intensive interactions between them. These results mean that for basic products and services, economies of scope have little influence on organizational structures. In other words, whether knowledge can be reused in different contexts or not, we are likely to observe specialized firms with few interactions among them.

One of the implications of this model for managerial decision making is concerned with the nature of organizational changes that accompany a modification of the position of an organization in the breadth and depth space. The modification of an organization in the breadth and depth space refers to a change in the knowledge base of the firm's products. In fact, innovation can be perceived precisely in this way: as a change in the knowledge composition of production. According to the resource-based view, as products become more and more complex, networks among firms get denser. However, here it is shown that the organizational impact of innovation depends on the nature of change in the knowledge base of products. A breadth-enhancing innovation (increase in complexity of the product) does not necessarily enhance networks among firms. On the contrary, if the innovation is at the same time depth-reducing, which results in increased chances for current knowledge in the firm to be reused, the managerial action can be to reorganize production within the firm rather than to search for complementary knowledge outside the firm boundaries. On the other hand, if the innovation is at the same time depth-increasing, which restricts the reusability of current knowledge within the firm, then the organizational response will be to revert to external sources of knowledge.

Last, but not least, the results of this paper should not be interpreted as *necessary and sufficient* conditions for organizational structures to emerge and to change. There are too many factors that influence the structure of organizations, one of the most important being the demand side. Nevertheless, in such a model, the impact of demand would largely be concerned with the allocation of products in the breadth and depth space. Rather, this model focuses on the influence of the mapping between knowledge bases and organizational structures.

In a world in which knowledge is at the core of both business and academia, and in which networks are the main mechanism through which knowledge diffuses, the impact of knowledge bases on organizational structures deserves much attention. The model points to some interesting results which may shed light on how organizations are influenced by knowledge.

Technical Appendix

The Model

There are M products, K knowledge types and N productive actors in an industry. Each actor i is endowed with a knowledge vector, assigned randomly (drawn from a uniform distribution) at period $t = 0$; k_j^i shows the level of actor i's knowledge in type j. We define the *expertise* of an actor to be that subject in which he or she has the highest knowledge. There is a knowledge type j for all i such that $k_j^i > k_m^i \; \forall \; m \neq j$.[9]

Given his or her knowledge vector, each actor in each period produces a type of good. But an actor can produce by him- or herself, or integrate his or her knowledge with another actor and produce jointly. The probability that agent i will produce good n is proportional to the weight of his or her expertise type *(j)* required by the good. For example, if product n uses 90% of the agent's expertise type j, then there is 0.9 probability that agent i produces good n. We adopt the term n-type agent if he or she produces good n. The amount he or she produces singly is given by $y_n(k^i)$.

Matching

Each agent, in each period *t,* chooses either to produce alone or to produce together with another agent. In making this decision, the agent's criterion is to increase the amount he or she can produce. Therefore, the agent compares the amount he or she can produce alone with his or her joint output with a proportion of other agents in the economy (about which he or she has information).[10]

Joint production happens through the integration of the knowledge of the two agents. When an n-type agent and an m-type agent form a pair, they produce both goods *n* and *m*. The quantities are found as follows. If two agents *i* and *l* collaborate (n-type and m-type respectively), their joint knowledge in category *j* is given by

$$k_j^{pair} = \max(k_j^i, k_j^l) \qquad \forall \quad j = 1,2......K \tag{1}$$

When an n-type agent *i* forms a pair with an m-type agent *l,* the joint knowledge vector, as given by Eq. 1 enters the production function of both goods *n* and *m*. If we denote the joint knowledge vector by k^{pair} the output is shared equally among agents[11] so that individual output shares are given by

$$y_{n,m} = \frac{y_n(k^{pair}) + y_m(k^{pair})}{2} \tag{2}$$

Therefore, agent i compares his or her single output (y_n (k^i)), with the amount that he or she can produce with other agents in the economy ($y_{n,m}$ (k^{pair})). Every agent has a preference listing (other agents ranked according to the maximum output they can produce with him or her). In practice, pairing in the population is made in such a way that *no two agents prefer each other to their current partners*. Contrary to the classical matching in *the marriage problem*, where there are two different populations, this is termed *the roommate problem* in the literature, where pairs are formed within a single population (Gale and Shapley 1962).

Production

We consider an economy in which the main input in production is knowledge.[12] We assume a Cobb Douglas production function where the amount of good *n* that can be produced is given by[13]

$$y_n(k) = \alpha \prod_j k_j^{\gamma_{nj}} \text{ where } \sum_j \gamma_{nj} = 1 \quad \forall\ n=1,2,........,M. \tag{3}$$

Here, k_j is the amount of knowledge in type *j*, and γ_{nj} measures the intensity of knowledge type *j* in good *n*. Since there are *M* goods and *K* knowledge types, the corresponding γ values for each good can be represented by an M × K matrix, which shows the weight of each knowledge type in each good. As demonstrated in Figure 4, and explained below, in one simulation run 36 matrices are taken exogenously. We assume that agents use all their knowledge in production. We also assume that demand is perfectly elastic so that profits increase monotonically with quantity.

Breadth and Depth

The breadth of a good is the number of different knowledge types that its production requires. It is given by the number of non-zero coefficients in the production function of the good (γ_{nj}). Because there are *five* knowledge types, there are four breadth values, since we exclude the case in which each product has only one non-zero coefficient. Depth measures the degree to which a knowledge type is used in different products. As two extremes, let us consider a high-depth good and a low-depth good. The former is the one in which a particular competence is dominant, and this competence is only weakly required in other products. A low-depth product refers to a case where the competences required can be used in different products with equal weight. We measure depth by the standard deviation of the coefficients in the production parameters. The higher the standard deviation among the coefficients, the deeper the knowledge base is taken to be. Based on these considerations, the exogenous production parameters are generated in the following way.

Mathematically, let us denote the number of inputs greater than zero for a product *i* by *n*, and the knowledge input coefficients by γ_{ij}, where $j = 1, \ldots, K$. Each of the patameters are generated randomly from different populations such that $\gamma_{ij} \sim (\mu_{ij}, \sigma_{ij})$.

We measure breadth by $n = 1/\mu$, and depth by σ_{ij}. To illustrate, let us take a good *i* with $n = 3$ and maximum depth. Here, the good takes three γs as input, and let us assume these are knowledge types $j = \{1,3,4\}$. Because we have maximum depth, one of the knowledge types is more dominant than others, say type $j = 3$. We draw γ_{i3} randomly from a normal population with mean $\mu_{i3} = 0.95$ and standard deviation s = 0.05. The other coefficients γ_{i1} and γ_{i4}, as an example, are drawn randomly from populations $\sim N(0.01,\sigma)$ and $\sim N(0.04,\sigma)$. When these three populations are aggregated, the mean is $\mu_i \simeq 0.33$ (so that breadth is equal to $n = 1/0.333$) and standard deviation is σ_{max}, which we take to be the depth of the knowledge base. If we have a good with $n = 4$, and maximum depth, we draw the coefficients from four different populations in such a way that the combined population standard deviation is σ_{max} as well. Following this procedure, we generate 36 matrices for one simulation. These 36 matrices correspond to *four* different breadth values, and *nine* different depth values. The reason for taking nine depth values is to reduce the difference between two consecutive depth measures as much as possible.

Learning

The knowledge levels of agents are updated in every period. Learning is assumed to be the result of gaining experience in production. We assume that agents are myopic, so that they do not adopt long-term strategies concerning what they can learn from their partners.[14] We also include an uncertainty term in the learning process, as the details are given in Eq. (4). The following function is used to update agent *i*'s stock of knowledge type *j*:

$$k_j^i(t) = k_j^i(t-1) + \theta_i y(t) g(t) \tag{4}$$

where

$$g(t) = \begin{cases} \delta_i(t) \text{ if } k_j^i(t-1) > k_j^l(t-1) \\ \delta_i(t) \dfrac{k_j^i(t-1)}{k_j^l(t-1)} \quad \text{else} \end{cases}$$

where θ_i measures the combinative capability of the agent, and $\delta_i(t)$ is an uncertainty effect. According to Eq. (4) learning is measured by how much an agent can make use of production $y(t)$. This is firstly a function of the capability of the agent, as given by θ_i. Second, it is a function of the relative knowledge levels between the partner agents.

Firstly, if agent *i* knows *less* than his or her partner before production, the amount of his or her learning is limited by his or her relative knowledge levels and his or her own capabilities. For example, if his or her learning capability is too high relative to the partner, he or she can even leapfrog the partner.

Secondly, if agent *i* knows *more* than the partner before production, the amount he or she learns depends on the agent's capability, an uncertainty effect and previous production level. This is because there is no other partner from whom he or she can learn, since she or he are already the expert. This is given in the first part of the function *g(t).* In this case,

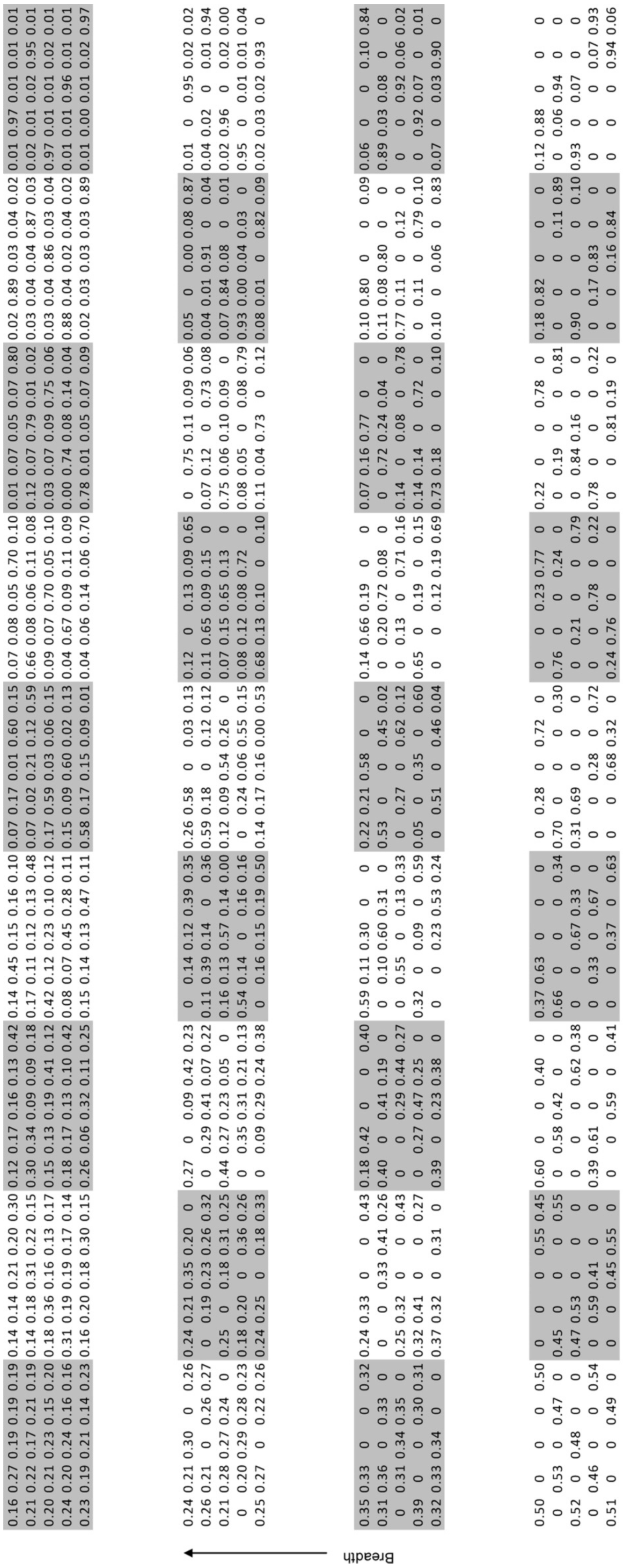


Figure 10.
An Example Set of Production Parameters

learning can be considered as the result of his or her own R&D. Here, uncertainty is given by the parameter $\delta_i(t)$, which is different for all agents in each period (the values of parameters are given below in technical information).

The knowledge levels are updated in all the knowledge types that enter the production function of goods *n* and *m*. That is, if the agents *i* and *l* are n-type and m-type respectively, knowledge is updated in all subjects in which γ^{nj}, & $\gamma^{mj} > 0$, $\forall$ j = 1, …, K.

Technical Information on Simulations

The simulation model consists of a population of agents endowed with knowledge in various types. In each period they form pairs, by selecting their partner according to their calculated joint production. Paired agents pool their knowledge according to Eq. 1. They produce together according to Eq. 3 and share total output according to Eq. 2. In the second period, they update their knowledge levels according to Eq. 4. Pairs are dissolved, and new pairs are formed with the updated knowledge levels.[15] Figure 4 in the main text provides the algorithm of the model.

The parameter values used in the model are as follows: M = 5 goods and K = 5 knowledge types.[16] Each of the goods is characterized by a vector of five knowledge input coefficients generated randomly using the procedure explained in section Breadth and Depth above. We perform 36 runs for a single simulation, each run corresponding to one matrix of knowledge coefficients. In each of these runs there are 5000 periods.[17]

We repeat this procedure 20 times, each with a different population. The results correspond to average values. The population consists of *N* = 50 firms. The uncertainty parameter $\delta_k(t)$ [0.95,1.05] and the capabilities are $\theta_k \in [0.8,1.2]$.[18]

Notes

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1 The technical explanation of the model, the parameters and the equations are provided in the Technical Appendix.
2 To partition the network into cliques, the software UCINET was used (Borgatti et al. 2002).
3 In 1946, the first electronic computer called ENIAC (Electronic Numerical Integrator And Computer) was announced by the US Army. For a history of the computer industry, see Campbell-Kelly and Aspray (1996).
4 For example, in 1972 the first personal computer, called ALTO, was developed in Xerox PARC, followed by the STAR system which incorporated for the first time graphical user interfaces (GUI), icons, folders, mouse, Ethernet, file servers and email.
5 The first luggable computer was the Osborne 1, introduced in 1981.
6 See Moggridge (2007) for the history of Grid Compass, and also for interviews with leading scientists and entrepreneurs in the computer history.
7 PalmPilot is one such product, developed by a group of engineers, who initially took part in Grid Systems.
8 For this purpose, some of the studies that the reader is referred to are Simon (1951), Madhok (1996), Kogut and Zander (1996), Conner and Prahalad (1996).
9 Specifically, $k^i_{jt} = k^h_{jt}$ means that agents *i* and *h* have exactly the same knowledge in type *j*. If $k^i_{jt} > k^h_{jt}$ If agent *i* knows everything that agent *h* knows in type *j*, and has some knowledge in addition (Cowan and Jonard 2003).
10 Here we assume that an agent knows about the knowledge levels of only a proportion of other agents, and makes a preference listing taking them into account. It is assumed that if agent *i* knows *j*, then agent *j* knows *i*.
11 We assume that the relative prices are unity, so that the amount of two goods can be added
12 The use of the term 'knowledge' can be thought of as human capital or competence, so that it accumulates as a result of learning.
13 By using a Cobb Douglas production function, we have the chance to differentiate between different sectors in terms of different ways in which knowledge can be embodied in products. This

is made by changing the parameters of the production function, so that some knowledge types are more dominant than others, and/or they are not relevant. This type of production function is employed widely in models in economic theory.

14 We assume a complex environment in which agents consider only the short-term joint production amounts, and that they cannot predict the amount of learning that will take place in the long run because of uncertainty. The nature of learning is incremental, and it is the result of learning by doing. This is mainly to avoid accidental/non-robust results which might occur if learning by one agent is too sensitive to a specific partner.

15 We take into account only bilateral link formation in a single period, but when sufficient time elapses these bilateral links form a network. Here our focus is on link formation rather than link preservation. This is especially valid considering the long-term effects of links. A partnership today has long-term consequences in terms of the knowledge that can be passed on to others. Moreover, we take into account the final cumulative networks, after which certain patterns emerge, i.e. the link formation is routinized in terms of the partner choices.

16 We select five goods and five knowledge types heuristically, to strike a balance between simulation running time and level of detail. Increasing the number of goods and knowledge types marginally, increases the simulation time in an exponential way (since there are a total of $20 \times 36 = 720$ simulations, the marginal increase in total simulation time is significant). For the purposes of testing the robustness of results, several example simulations were run with up to 10 knowledge and good types.

17 In the model the simulation time does not correspond to real time. The amount of learning happening in one period is limited, so the time frame is in fact intended to be very short. Moreover, at least $50 \times 50 = 2500$ periods are required so that all agents have the chance to select, at least once, all other agents.

18 These parameter ranges are selected on the basis of 1) mathematical feasibility and 2) strength of the results. Changing the parameter ranges strengthens or weakens the results obtained, rather than changing the *patterns* observed in the breadth and depth space. As an example, increasing the uncertainty parameter range by 0.1 increases the absolute value of the network density in all regions. The same holds true for the capabilities parameter. This is because learning becomes more uncertain, which gives rise to more frequent changes in partners. This is why the uncertainty parameter was kept at a narrow range, so that we can both understand the mechanisms which produce these results, and at the same time provide sufficient level of randomness.

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