Technological change and the vertical organisation of industries *

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Abstract

The vertical scope of a firm, that is, which components or segments of the production processes are kept in–house and which are outsourced, is variously considered as depending on cost and/or technological conditions. Most of the literature focuses on the incentives for an individual firm facing exogenous competition and technological opportunities.

In this paper we consider the problem from the perspective of the whole industry: in which respect firms organisational behaviour depends on the industry technological evolution and aggregate structure, and how firms innovation and organisational behaviour affect the industry structure.

We build an evolutionary simulation model of an industry where competitors decide the number of internally produced components. We relate the industry average value of market outsourcing to the technological conditions prevalent in the industry. The results from the model shed light on a number of (apparently) contradictory suggestions in the economic and management literature.

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1 Introduction

Since the advent of the capitalist mode of production, the way in which production itself is organised has continuously evolved through different competing structures. Across time and sectors firms compete and tune their organisation to what they perceive to be the most efficient form, given the state of the markets and technologies they deal with. Firms restructured into Fordist organisations when economies of scale and routinisation were perceived (rightly or not) as the key to competition. Some firms remain small and concentrate on niche specialisation. Others aim at greater flexibility and just–in–time calibrations of production.

The various theories of the firm provide convenient explanations for any of the organisations adopted by firms at different points in time. Our aim in this paper is to investigate how the organisation of an industry — as the aggregation of firms' organisation — in terms of vertical integration/specialisation of production stages, can be influenced by the dynamics of technological opportunities and competition, and how it evolves as a consequence of changes in product technology. We refer to several approaches to economic theorising, using some of the more robust results in the literature to build our model assumptions, and challenging the available conjectures and hypotheses with our results. Our study makes a contribution to the literature that defines industrial organisation as the "institutional structure of production" (Coase 1992), meant as "the division of labor across the vertical divide and between firms" (Jacobides and Winter 2005, p.397).

We develop an agent–based simulation model to relate the institutional structure of an industry, and its changes over time, to firms' individual behaviour. A population of firms technologically heterogeneous compete in one industrial sector via product innovation. The value of a product, defined in terms of user characteristics, can be increased by innovating in individual modules. The relations between the technologies of these modules define the product architecture and level of modularity. Firms may decide to produce internally or outsource a number of modules. When they opt for the latter, they lose control of the technological innovations in the module, incur some market transaction costs, but gain from the economies of specialisation reaped by the supplier. Nonetheless, the weak modularity of a good limits the possibility of decomposing the technological problems, and makes product innovation a complex task. Therefore, exogenous changes at the technological frontier require firms to continuously adapt, and seek a superior trade off between savings on costs and mastering the product architecture.

A thorough analysis of the results, properties, and dynamic mechanisms in our model allows us to shed some light on the relation between technological change and the structure of production. We first explain the general behaviour of the model (and firms) under particular technological dynamics. We then use the results to explain their micro behaviour through an extensive analysis of the relation between the rate and pace of technological change, and the organisational structure. Finally, we use the model to analyse, and provide some intuitive explanations about, the long term cyclical restructuring of industrial organisation along successive product life cycles.

The paper is structured accordingly. In section 2 we locate our contribution within the existing literature(s), and make explicit the questions we want to address. In the next section 3 we describe the model and its assumptions. In section 4 we analyse the results from the model with reference to the existing literature and our assumptions. Finally section 5 draws some conclusions and briefly suggests some of the multiple possible extensions of this work.

2 Innovation and the organisation of industries: the need of a complex approach

The good purchased by a final consumer may be produced entirely by a single integrated firm or assembled from components purchased on the market for intermediate products. And, of course, any combination of the two extremes is also possible, with firms producing some components in house, selling some of them to competitors and buying others. A long tradition in economics devoted to studies of vertical (dis)integration refers to agency and market transaction costs (e.g. Coase 1937, Williamson 1975). Indeed, the heterogeneity in the composition of industries and in the organisation of production, over time and across sectors, suggests that an explanation that accounts for the technological organisation of production is (also) required (e.g. for discussion Richardson 1972, Dosi and Marengo 2002). In a nutshell, the degree of vertical integration in an industry is related to its technological regime: the cognitive complexity of the technology, the rate and pace of evolution of standards and technological regimes, and the relative competencies of specific firms to deal with the technology, compared to their competitors (Marengo and Dosi 2005).

However, despite an increasing focus of the literature on the role of technology in shaping industrial dynamics and organisation, the nature of this relation remains unclear, even in terms of whether overall more complex technological challenges induce firms to increase or reduce integration (Brusoni, Marengo, Prencipe, and Valente 2007). Is it the form of technological *change* that influences the degree of integration among the firms in an industry, as Acemoglu, Aghion, Griffith, and Zilibotti (2005) and Robertson and Langlois (1995) suggest, though from quite different perspectives? What is the expected evolution of the industrial organisation throughout the life cycle of an industry? Can we expand on and generalise about Klepper (1997) evidence on industry dynamics, providing a general framework and testable results? If the organisational structure evolves with the technology and product structure, what are the microeconomic mechanisms that explain their interdependence?

In order to answer these questions, we need to turn the argument on its head, as the relation between organisation and technology runs in both directions: i.e. changes in firms' organisational arrangements affect their technological opportunities and outcomes (e.g. Robertson and Langlois 1995). For example, when firms are faced with rapidly evolving markets, their suppliers may lose track of the technological evolution of the product's characteristics in the final market and, in the case of a highly integrated good, of the whole product architecture: economies of specialisation are then offset by 'dynamic transaction costs' (Langlois 1992).

Indeed, the influence of the organisational structure on a firm's technological outcome is affected by the degree of complexity of the product in terms of its (non–)modularity (Langlois 1992, Brusoni and Prencipe 2001, Ernst 2005).

Highly integrated products require search heuristics over complex technological landscapes, which cannot be efficiently explored with modular strategies (Kauffman, Lobo, and Macready 2000). Unless a — fully informed — supplier of a specialised module is able to keep track of the integral architecture, and offer a user–tailored technology to a client, *as if* it was part of it. Indeed, the same module may not integrate with the technology of other potential clients, unless it emerges as a standard interface (David and Greenstein 1990); however, standards change throughout product life cycles. Therefore, we can observe the processes of specialisation and outsourcing as well as firms that re–integrate previously outsourced components (e.g. Cacciatori and Jacobides 2005) as an outcome of the interaction between the organisation of production and the product technology.

We can find three possible answers to our questions, in the literature. First, following from Aoki (1986) seminal paper, a number of theoretical and empirical works have focused on the relationship between the hierarchical scope of decision making and the intensity and frequency of technological 'shocks'. Vertical integration is found to be preferable in situations of system–like technological advances, changes in individual modules of integrated goods and predictable demand changes. On the other hand, *when either the technology or demand are evolving rapidly, vertical integration will hamper the exploration of new modular solutions, and vertical specialisation will be preferred* (Robertson and Langlois 1995). As suggested above, the higher the product modularity, the more this is the case (Langlois 1992). Vertically flexible structures also avoid the switching–costs that "governance inseparability" imposes on firms (Mahnke 2001).

Second, firms' *distance from the technological frontier affects decisions about their vertical integration* (Acemoglu, Aghion, Griffith, and Zilibotti 2005). By mitigating the managerial overload of production and innovation activities, vertical specialisation favours the performance of innovative firms close to the frontier. Conversely, when firms are located far from the technological frontier, imitation activities are more important, and coordinated vertical integration is preferred.

Third, *organisational structure is heavily influenced by the stage of the technology within the product life cycle* (Klepper 1997, Marengo and Dosi 2005). Contributions along these lines can be found in the transaction cost literature (Aghion, Bloom, Blundell, Griffith, and Howitt 2005) and the competence based literature (Utterback and Abernathy 1975, Abernathy and Utterback 1978). Within the latter tradition, Foss (1993) argues that the introductory stages of the life cycle increase vertical integration due to the need to overcome the slack in market mechanisms for innovative products and components. In fact, new products may require an array of components substantially different from those available in the market. Conversely, in the mature stages, the increased demand for standardised components may induce a vertical division of labour, reducing production costs through specialisation. This is especially the case in declining stages, when technological change is slowing, rendering the interfaces among the product's components fairly stable, while the relative competences diffuse both upwards and downwards. What occurred in the computer industry is an example of this kind of cyclical pattern (Bresnahan and Malerba 1999).

In conclusion, the literature suggests that the vertical organisation of a firm is influenced by, and wields influence over, the nature of technological change.

Also, the literature shows that there are historically recurrent features in relation to the type of technological change and the overall organisation of industries. Our aim is to explain (at least partially) how individual firms interact within an industry, in order to generate aggregate patterns compatible with those generally observed in the empirical studies. For analytical convenience we consider only one direction of the two–way interaction between technological change and industrial organisation, studying how the (assumed exogenous) pace of technological change affects the behaviour of firms in order to endogenously determine specific (vertical) organisations at industry level. This is not to deny that organisation affects *innovation* at the firm level, which is included in the analysis. However, we do not consider how firms' innovative activity affects the *technological change* at the industry level.

3 The model

This section describes how we model the relation between a technological landscape and a market organisation. The rationale for the model, its main hypotheses and the behavioural assumption are discussed (Section 3.1) in the light of the theoretical background and empirical evidence outlined above (Section 2). We then provide a verbal description of the model content. Interested readers can find a formal description of the model and detailed analysis of the results, in Ciarli, Leoncini, Montresor, and Valente (2007b).

Four main branches of the literature underpin the model's features. Firstly, we adopt an integrated approach, combining *transaction costs* and *capabilities*, as the determinants of the industry's institutional structure. Accordingly, we assume that the distribution of production capabilities in an industry, along with transaction costs, explains its organisational and technological changes (Dosi and Marengo 2002, Jacobides and Winter 2005).

Secondly, firm behaviour is modelled from an *evolutionary perspective* (Nelson and Winter 1982): boundedly rational firms, with information mostly limited to the neighbourhood of their knowledge set, follow path dependent production and search routines, which translate in to problem–solving activities and the definition of heuristics (Dosi, Nelson, and Winter 2000). The extent of those activities defines their capabilities (*ex–post*).

Thirdly, we make use of the growing literature on modularity (Brusoni and Prencipe 2001), and its opportunities and limits for the organisation of production (Ernst 2005).

Finally, the complex interaction between (non–)modular dimensions requires heuristics to decompose the problem into sub–problems (Simon 1969). In particular in the innovation process, the way in which a new problem is posed and decomposed, and the structure of the related (collective) problem–solving activity, define its basic ingredients (Marengo, Dosi, Legrenzi, and Pasquali 2000, Brusoni, Marengo, Prencipe, and Valente 2007).

3.1 The general setting

We consider the market for a final product composed of a number of modules (or components). For each firm the quality and price of its product depend on the quality and the cost of production or purchase of the modules. Therefore, producers' activities are oriented to improving the quality and reduce the costs of the modules, under the constraints imposed by the prevailing technological architecture, economic opportunities and institutional structure of production. A demand function translates the modules' technologies and costs to market shares. Exogenous dynamics push the technological frontier, influencing the performance of the technologies. Firms innovate in their product (i.e. the modules that comprise it), and decide which modules should be produced in–house and which should be purchased in (endogenously forming) intermediate markets. Our results focus mainly on the degree of vertical integration as measured by the average number of components produced in–house by the firms in the market.

In each time period the model dynamics involves the following steps:

1. given the market shares resulting from firm behaviour and technological achievements in the previous period, demand is computed and relevant sales allocated to each firm;

2. firms perform technological searches, in an attempt to increase their competitiveness by testing an innovation on a randomly chosen module;

3. with the same aim firms reconsider the organisation of production, testing the outsourcing (internalising) of a randomly chosen module currently produced internally (externally);

4. finally, the value of their production is updated, in terms of both costs and quality.

In the first two sets of simulations we make the rather extreme assumption that firms that supply modules to clients may not innovate in these modules; innovation is restricted to the modules produced in house. This assumption is based on the principle that firms that concentrate their production on intermediate components lose contact with the technological frontier of the end product. In the last set of simulations we relax this assumption. In any case, the results are only marginally affected by this assumption, as we will show in the discussion of the results.

The following paragraphs describe the main implementation features applying to the different elements of the model.

3.2 Demand

The competitive setting is defined on three levels. First, the technologies adopted by a firm for each component are translated into different quality dimensions, or user characteristics (Lancaster 1966). The relation between technologies and quality is complex in that it includes a degree of interdependency between modules (see below). Second, these characteristics and the price are converted into a measure of the firm's performance or competitiveness, assuming, without any loss of generality, that characteristic values are positively related to performance, while price is negatively related. Third, the normalised performances of all firms involved determine their market shares, while the total demand level is an increasing function of the average level of firm characteristics.

Both firms' individual sales and aggregate demand are assumed to be "sticky", changing only partly from their present values to the target value, which is eventually reached only if the target level is kept constant for a sufficiently long period. This assumption is not relevant as far as demand levels (aggregate or individual) are concerned, but slows down excessive (and implausible) reactions to demand changes. Without this assumption earlier innovators would have excessive advantage compared to innovators introducing equivalent products even immediately afterwards.

Competitiveness is pursued by means of three interrelated strategies. First, technological improvements allow the production of higher quality goods, increasing the appeal of the firm's offer with respect to competitors. Second, savings on production costs are achieved through economies of scale and learning–by–doing.[1] Third, organisational change, such as the decision to outsource/integrate the production of a module, influences the technological quality and the cost of the modules concerned and, consequently, of the whole product.

3.3 Technological landscape and innovation

Firms can modify their products in three ways: by innovating in a component and "discovering" a new technology; by outsourcing one or more components to an external supplier; by internalising a previously externally sourced component.[2] Whichever case applies, firms adopts an innovation if it increases the overall performance of the good via an increase in the average quality of its user characteristics. Decisions are taken by testing changes in one component at a time, so that, since the product is not completely modular, the goal of increasing (local) performance may well increase the distance from the global optimum. Following we explain the innovation dynamics, while outsouring and internalising are described in section 3.5.

Innovation mimics exploration dynamics in complex technological landscapes, where the landscape dimensions are represented by modules, and the *fitness* is the quality of the product. Landscapes are built so as to admit a single smooth peak, but the pattern leading to the peak by changing one component at a time is rather narrow and tortuous. In particular, a firm located in a particular position in the landscape (that is, with a given set of technologies for each of the modules) may find performance–improving a step that brings in a location further from the global peak. The properties of complexity implemented in the model are similar to those of an NK landscape with low correlation (Kauffman, Lobo, and Macready 2000). That is, the same change in one component may be fitness–increasing or fitness–decreasing depending on the state of the other components. However, in our context, NK models are rather limited because they represent only binary values for components (preventing the representation of ever–increasing variables), and admit only on–off types of interaction: two modules are either interdependent or they are not. We use a more efficient and flexible Pseudo–NK (PNK) model to define a semi-modular (and semi-interdependent) technological landscape. This model retains the concept of interdependency of the original NK models, but allows for real value variables (suited to representing unlimited technological states of a module) and graduated interdependencies (all modules interact with each other, but to a partial degree). Moreover, the PNK model allows us to exogenously determine the

[1] We ignore agency costs, which amounts to assuming that agency costs affect all firms equally and the transaction costs refer to their net effect after agency costs.

[2] Note that we use product component, module and input interchangeably.

optimal location of the landscape, which is important to show the movements in the technological frontier (i.e. the optimal location). The PNK configuration we adopted allows for generally reaching the global optimum by means of a single–module mutation, though the required path may be rather narrow, and random search might point in the "wrong" direction (far from the optimal point), especially when performed far from the optimal location.[3]

A firm innovation then consists of randomly selecting one module and randomly modifying its state, that is, applying a new technology in the module in the neighborhood of the current state. The new module is then tested by evaluating the qualities of the product. If the market performance (price and user quality) of the new product is greater than that generated without the innovation, the new technology is accepted and immediately replaces the previous one. Given the semi–modularity of the technological landscape not all accepted (performance increasing) innovations drive the module closer to the optimal technology (global maximum) as defined by the frontier, since this will depend on the state of all the other modules.

A crucial aspect of the model consists of exogenous movements in the technological frontier, represented by random shocks affecting the optimal location of the technological landscape. The values of the optimal technologies for all modules are modified with the following rule:

$$c_t = \begin{cases} c_{t-1} + \zeta & \text{with probability } Z \\ c_{t-1} & \text{with probability } 1 - Z \end{cases}$$

where $\zeta = \upsilon \cdot \omega$; ω defines the *magnitude* of technological change, Z its *frequency*, and $\upsilon \sim U[0,1]$ is a uniform random variable. The implication of this representation of the frontier is that it has no upper limit. Firms adopting a given constant technology will see their performance falling as the frontier moves further away, forcing firms to innovate (change the technology of their modules) just in order to maintain their distance from the frontier.

3.4 Costs

The competitiveness of a firm depends on the technological quality and price of its products. Prices are determined on a costs–plus basis, with an equal mark–up for all the firms. Costs are computed independently for each module, and depend on two factors: economies of scale and learning–by–doing.

When a module is produced in–house, economies of scale set in. This effect, as we will see, is crucial in determining suppliers advantage in the case that producers also sell the module to other producers, increasing the scale. Moreover, other things being equal, learning–by–doing decreases the cost of producing a module with a given technology, increasing the quantity produced. As innovations to the module are introduced, the lower costs associated with the old technology disappear, provoking a path of new learning. This effect balances out lack of innovation, since it is assumed that "frozen" technologies allow for improvements to their production efficiency.

On the other hand, prices for modules sold to other producers include a mark–up on production costs (assumed to be, ceteris paribus, identical for both

[3] An exhaustive discussion of the PNK properties can be found in Valente (2006) and Ciarli, Leoncini, Montresor, and Valente (2007a) describes a similar version applied to a market.

internal use and direct sales). Therefore, purchasers of intermediate components will have to charge a higher price to consumers, since on the imported modules there will be two mark–up's charged. This is an implicit form of transaction costs, in that only relatively higher quality products and/or lower cost products justify the inclusion of bought in components rather than internally produced ones.

3.5 Outsourcing and integration

We assume that firms are rather conservative concerning changes affecting their vertical organisation, and are unwilling to introduce an institutional or organisational innovation unless it is clear that it will provide long–term advantage. This is because changes to the organisation incur adjustment costs, both direct costs and those related to the risks associated with irreversible decisions (or reversible at a high cost).

As mentioned for the innovation dynamics, firms are able to consider the outsourcing (or integration) of individual modules at a time. The outsourcing (or integration) of a particular module occurs when several independent tests, conducted at different times, consistently indicate that such modification would increase the firm's fitness. These tests compare current competitiveness on the market — i.e. with the module in question, outsourced (or produced internally) — with forecast competitiveness under a different production arrangement (respectively internal or outsourced). A change in the organisation is then made only after several consecutively positive tests.

Firms outsourcing a module (or testing this hypothesis) consider the best supplier available in the industry, with a technology compatible with its product architecture, i.e. in the neighborhood of the current technology of the module; suppliers cannot refuse to provide a requested module. Having outsourced a module, the firm will continue to explore its technology, evaluating potential improvements with those achieved by the supplier. When the supplier's technology no longer suits the firm's product architecture (incurring a fitness reduction), the firm will start evaluating a change of supplier or the reintegration of the module (occurring only after several consecutively positive tests).

4 Technological dynamics and industrial organisation: simulation results

In this section we provide some simulation results that add to our understanding of the dynamics of technological change and how it affects the organisation of an industry. Although quite complex, the model is not meant to provide an even vaguely realistic representation of specific (or, for that matter, generalised) industries. The objective is to assess the impact of a few technological conditions — i.e. technological shocks, distance from the technological frontier, product life cycle — on a few variables — i.e. industry organisation and concentration. The analysis includes only those elements relevant to our hypotheses, and ignores aspects which might play a relevant role and which clearly need to be treated in future research to enrich our results. For example, we ignore the financial aspects of innovation: our firms have virtually identical innovation resources independent of their past and present profits. We also prevent non–performing incumbents from exiting the market and ignore the possibility that there may be new entrants. Finally, consumer demand relies on constant preferences, despite changes in the technology.

Our simulations should be interpreted as logical tests, which allow us to assess statements under *ceteris paribus* clauses, although we are aware that these constraints could not apply to a real case. Nevertheless, we believe that our conclusions, because they are based on a robust chain of logical consequences — as embodied in a computer simulation, help to make sense of some of the economic mechanisms that contribute to explaining a number of real world cases.

As in any mathematical model, the results are based on logical derivations of the model's hypotheses; they are consequences that can be traced back to the assumptions in the model. The use of agent–based simulations allows us to investigate non-obvious dynamics from the interactions among economic entities. We provide a detailed description of the events simulated, supported by graphical representation. Detailed numerical analysis of the model properties is not included here, but is available from the authors on request. The results should be seen as being based on virtual rather than real case studies, which can be analysed in detail, can explain the micro mechanisms behind the properties of industry organisation and allow to extensively studying the impact of technological conditions. Their relevance is restricted to the phenomena that *ceteris paribus* are similar to those in the empirical observations.

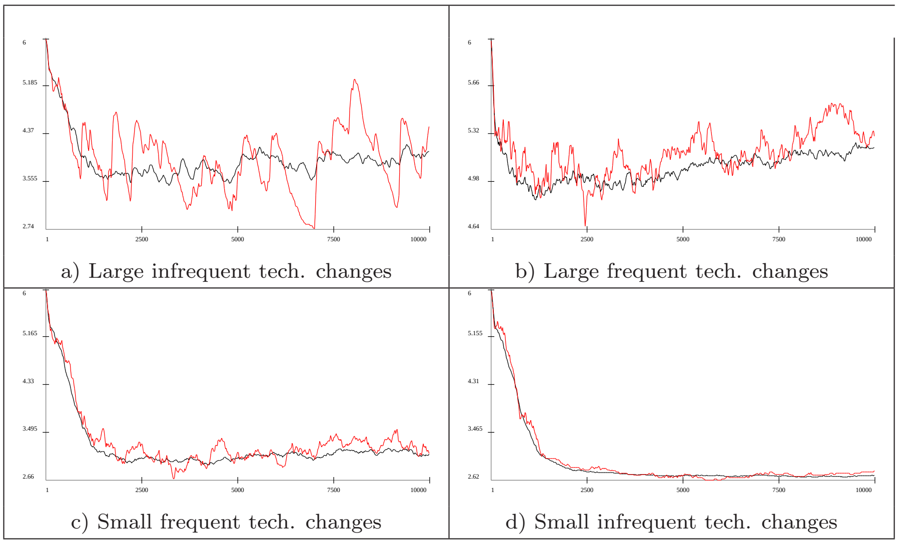
We thus allow for a 'test' of the conjectures and hypotheses — built on empirical case studies — reviewed in section 2, and point to their logically consistent explanations. We show results for changes in industrial organisation in four 'extreme' technological settings, and use them as explanatory examples. These provide intuitions to explain the following analysis of the properties of the relation between technological dynamics and industrial organisation,

We consider an industry comprising 50 firms, each selling a six-module product. At the start of each simulation we assign to each firm an initial identical market share and a randomly determined technological level for their modules. We assume that firms are fully integrated at the start of the simulation period, that is, they are producing internally the six modules comprising the final product.

4.1 Types of Technological Dynamics: Examples of Organisational Change

We generated four series of simulation runs, where each series (an average of 10 independent runs) is assigned a different dynamic of technological change. The four technological dynamics represent the four cases associated with frequent/infrequent and small/large changes in the technological frontier. Figure 1 shows the cross–firm average number of modules produced internally, i.e. not purchased from external providers. For each setting the graphs report both the series for a single simulation and the values averaged across 10 independent simulation runs.

All the simulation settings show an initial drop in the number of modules produced internally: given the initial random allocation of module technologies, most firms immediately recognise that they could improve the performance of their product easily, by outsourcing the 'worst' component(s). The initial



a) Large infrequent tech. changes
b) Large frequent tech. changes
c) Small frequent tech. changes
d) Small infrequent tech. changes

Figure 1: ***Evolution of the average number of integrated components (vertical axis) along simulated time (horizontal axis)****. The dark series reports the average across 10 independent simulations and the lighter series refers to a single example run. The four graphs refer to the reported technological dynamics, i.e., exogenous movements of the technological frontier.*

phases of the simulation runs, in effect, represent a barter based on technological comparative advantages, which adjust for the inconsistencies in the random initialisation. The extent of outsourcing, then, depends on the technological environment.

Case (a), representing infrequent and large movements in the technological frontier, generates relatively high integration (firms producing on average about four modules), but also high volatility, with large and persistent departures from the long–term average. If we look at the 'component's markets' (i.e. which firms are selling which modules to which other firms) we can understand the reason behind this aggregate result. A relatively long period of technological stability allows a few firms to specialise in components technologically compatible with a large number of other firms, which are induced to externalise the production of those modules to reap the advantages of economies of specialisation — learning and scale, reducing their costs. A large jump in the technological frontier disrupts technological standards and forces firms to re–consider the technologies acquired for most of their modules. In fact, in the case of most, if not all components, in order to innovate firms need to control the product architecture. This results in a sudden increment in the average number of components. As firms again approach the technological frontier, the industry re–organises on a cost–saving basis, and externalises many components, until a subsequent burst of technological opportunities.

The oscillating pattern shown in case (a), becomes more frenetic, less volatile (less dramatic peaks) and a constantly increasing pattern of vertical integration under setting (b), where large leaps in the technological frontier are much more frequent. After some initial outsourcing based on exchange of more efficient modules, vertical integration starts to increase constantly. Large and frequent movements prevent the advantages of specialisation (learning and economies of scale) from compensating for the higher capacity of integrated firms to explore the technological landscape. This setting, therefore, generates the highest level of integration, and consequently the lowest level of inter–firm trading of individual modules. It represents a sort of market where each firm adopts a proprietary architecture, as if, lacking a common standard, it were impossible for any firm to integrate any other producers' modules.

In settings (c) and (d), where technological change is small (100 times less with respect to in (a) and (b), firms, on average, find an easy way to accommodate to changes in the technological frontier. Therefore, economies of specialisation dominate, and outweigh the cost of market transactions: most firms merely assemble components produced by a few, specialised producers, while keeping in–house the production of more strategic components, which they supply to other firms. These are the components which, for random reasons, acquire a technological level that is compatible with the product architectures of a sufficient number of outsourcing firms. Sales then further promote learning and scale economies, increasing the attractiveness of a specific module and even for firms for whom the technology is only partially compatible. Overall, the level of intra–industry trade is high. The possibility of incompatibility generated by movements in the technological frontier is higher in (c), where movements are more frequent, and cumulated small changes suddenly render the technological level of a popular component irrelevant, despite its low cost. However, when all modules are roughly equivalently upgraded, the opportunities for exploiting cost–saving dynamics re–emerge. Cost–saving attitudes may dominate since technological excellence is easy and widespread. The trade dynamics in the intermediate markets are interesting in showing that,[4] on average, across the four scenarios — across simulation runs and firms, certain components are more frequently outsourced (traded), than others. This is due to the overall product technological architecture, which defines which components are more strategic, in that they make a higher contribution to satisfying consumers' preferences.

To summarise, we find that firms' *distance from the technological frontier crucially affects their decisions about vertical integration* (Acemoglu, Aghion, Griffith, and Zilibotti 2005). When the distance increases due to an exogenous change in technological opportunities, and in the economic conditions assumed in the simulations scenarios, firms become vertically integrated organisations. The trade–off between managing product innovation and the economies of specialisations plays a major role in determining the evolving institutional structure of the industry.

4.2 Types of Technological Dynamics: Extended Analysis

We next explore the relation between the dynamics of technological change and the average number of components internalised. From section 2 we know that *when technology evolves rapidly, vertical specialisation is preferred* (Robertson and Langlois 1995). Figure 2 presents the results of a detailed analysis of an extended range of the parameters governing frontier dynamics.

This allows us to provide a more detailed answer to the questions relating to

[4] Figures available from the authors.

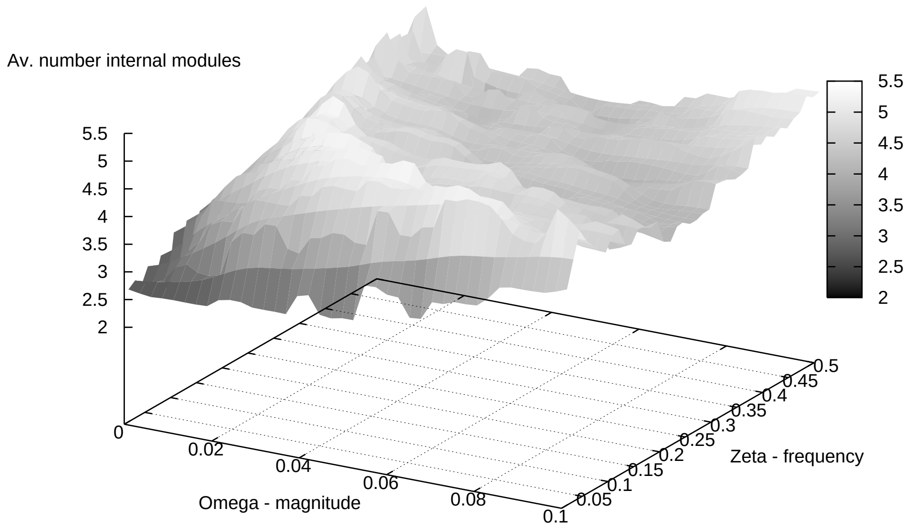


Figure 2: ***Technological change and firm organisation***. *Average number (and cross–firm variance) of in–house components for different width (ω) and frequency (Z) values for technological change (values computed at the time step 10,000). Each parameter was tested for 20 values on its range (see axes) and, for each of the 400 combinations, we computed the average value (at time step 10,000) over 10 simulations.*

industry structure and technological environment, i.e., whether increasing technological opportunities induce firms to increase the integration or specialisation of the production process. Rather surprisingly we observe a non–monotonic change in the average level of components when we move from stable to unstable technological environments. There is thus no unequivocal answer, since both phenomena occur, as suggested by the (apparently) contradictory results in the literature.

However, as in the specific scenario case discussed above, firms are forced to integrate when the magnitude *and* frequency of changes at the technological frontier leave no opportunity for potential suppliers to identify a component compatible with the — fast and radically changing — products of potential clients (right corner on the ω–Z plane). It is also the case that, for increasing levels of magnitude and frequency of technological change, up to intermediate levels of their *combination*, most firms prefer to integrate in order to explore the technological landscape more fully, without being constrained by external modules where they have little or no possibility of innovating.

However, when technological change reaches an intermediate level, the Robertson and Langlois (1995) hypothesis seems to explain the evolution of industry structure: *when either the technology or demand are evolving rapidly, vertical integration will hamper the exploration of new modular solutions, and vertical specialisation will be preferred.* It is relevant to mention that this convex relation for intermediate to high levels of ω–Z *combinations* is found for average levels of product modularity.[5] In fact, the explanation provided by the micro dynamics in our model differs slightly from Robertson and Langlois (1995) in that firms find it profitable to dump parts of the production process in order to concentrate their innovative efforts on a few components, rather than to improve their capability to explore new modular solutions — which, incidentally, would be a valid explanation only for high levels of product modularity. In other words, for intermediate to high levels of technological change firms are no more able to innovate successfully in some particular components (either because they have been externalised, or because they are locked into some local optimum[6]), and concentrate their technological efforts on the ones where they can successfully innovate. Given the stochastic nature of product innovation and, to a minor extent, organisational change, under those technological conditions firms behaviour differs consistently: few firms find compatible suppliers that allow for major outsourcing, while others need to rely entirely on internal production. Figure 3 depicts the extent to which innovation and organisational strategies change across firms.

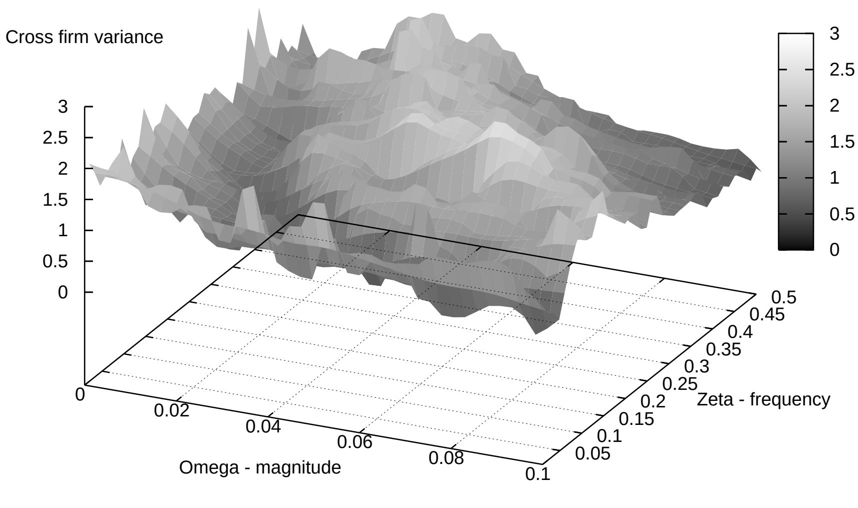


Figure 3: ***Variance in technological change and firm organisation***. *Cross–firm variance in in–house components for different width (ω) and frequency (Z) values of technological change (values computed at the time step 10,000).*

[5]It would be interesting for future work to test where the first peaks (see figure 2) would occur in the case of highly integrated and highly modular goods.

[6]See Ciarli, Leoncini, Montresor, and Valente (2007a) for an analysis of firms technological exploration of 'complex' technologies.

4.3 Industrial evolution and technological change

Our simulation model represents the rate of change in the technological frontier as an exogenous phenomenon, independent of firms' actual technological performance in the simulated market. This assumption is obviously unrealistic, given that the set of technological opportunities is jointly generated by the collective efforts of profit–seeking actors and other institutions. However, for analytical purposes, this assumption is useful since we can appreciate the effects of the rate of change in an industry without the results being influenced by how the model aggregates industrial innovative activities to shape the pattern of the technological frontier. In the following we test the model when the pattern is exogenously forced into various trajectories, mimicking those that occur in a product life cycle.

A small but growing literature is based on a modelling approach labelled *history friendly* (Malerba, Nelson, Orsenigo, and Winter 1999), in which highly abstract simulation models are calibrated to observed dynamics, to generate simulated histories which closely resemble actual observed patterns in a specific industry. We conduct a similar exercise, though with some important differences. Our model aims at replicating some very general properties of a large number of industries, each substantially different in terms, e.g. of the nature of the technology, the competitive and institutional environment, etc. It would, therefore, make little sense to calibrate this partial model, implementing only a small set of the elements composing real–world systems, to replicate numerical observation collected from a real world industry. However, the general pattern of the technological frontier during the evolution of an industry is acknowledged to follow very similar patterns across a large number of industries. Therefore, we can aim at reproducing more general functional, or qualitative, properties concerning the elements implemented in our model.

Table 1. Technological frontier and product life cycle patterns. Expected movements in the technological frontier.

Frequency / **Amplitude**	*Infrequent*	*Frequent*
Large	Phase I	Phase II
Small	Phase IV	Phase III

Instead of calibrating our exogenous parameter upon observed ones, we break down the simulated period into four phases, each characterised by a different technological frontier dynamic, which reflects the three typical phases in the product life cycle. The magnitude of the movements at the frontier is relatively high in the first half of the simulated period, decreasing in the second half. This means that in the early stages of product evolution in an industry, there are opportunities for large technological advancements, while in the later stages, when the technology is approaching maturity, these opportunities shrink. In terms of the frequency of frontier movements, we assume that this is low in the first and fourth period, and high in middle two. This assumption is based on the higher frequency of technological improvements we can expect when a new technology has become established in an industry (after the earlier paradigmatic change) and before diminishing returns reduce the incentives to invest in a mature technology. These effects together generate the four phases presented in table 1. As it will be more clear from the analysis of the results, we decompose the initial phase of a product life cycle into two different patterns of the technological frontier, Phase I and II.

Next, we then analyse the behaviour of an industry through the stages of the life cycle, discounting our assumption that component suppliers cannot innovate in modules sold to other producers. Figure 4 depicts the results of simulation runs for exogenously induced patterns of change in the technological frontier through the different phases. We impose abrupt changes in the frontier dynamics, i.e. the passage from one phase to the next is not smooth (as we might expect in the real world), but takes place within a single period. The graph reports the average number of internally produced modules in the industry at each time step. its variance across firms, and their market share in the final market (average values over 10 independent runs). The configuration of the model is otherwise the same as in the previous simulations.

The four phases are easily identified in the graph from the changes in the frontier dynamics occurring at time 10,000, 20,000 and 30,000. In phase I the number of internally produced components falls steadily; phase II induces a sudden change, by tripling the average in–house activity; phase III induces another fall in value and, finally, phase IV maintains a low level of vertical integration.

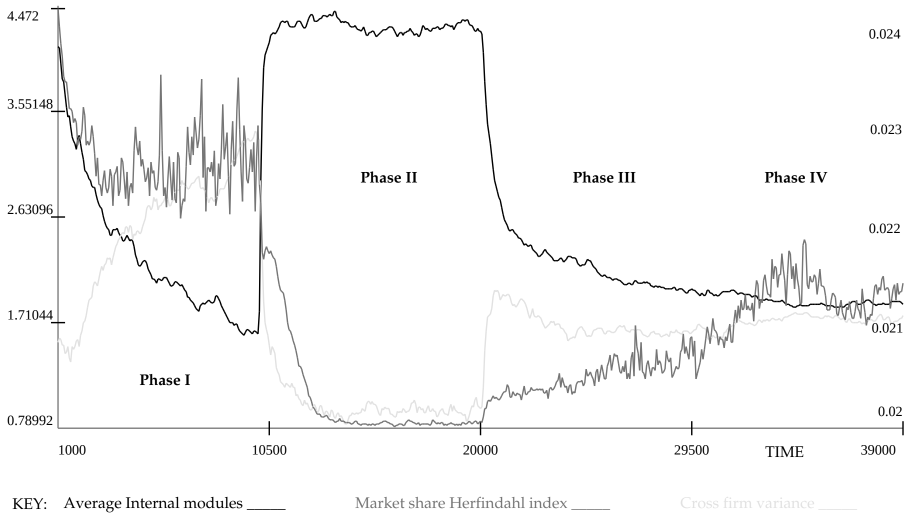


Figure 4: ***Industrial organisation and product life cycle***. *Evolution of the average number of integrated components (black), firms market share Herfindahl index (grey) and cross–firm variance of internal components (light grey) across different (exogenously determined) expected changes in the technological frontier: I) large and infrequent; II) large and frequent; III) small and frequent; IV) small and infrequent. Average values over 10 independent simulation runs.*

The first phase is assumed to stylise the transitory phase from a mature product to a paradigmatic shift. In an economy where suppliers also innovate, the industry (endogenously) reacts by increasingly segmenting the production process and generating novel markets for each component. The producers are initially diversified because of their different initial positions in the technological landscape, and they are further differentiating by the randomness of their R&D results. Typically, in our model, the same innovation developed by two firms may be adopted by one and rejected by the other because of differences in related components. At the industry level we see that most firms specialise in supplying few components to others, produce internally only a small number of components and rely on external suppliers for the rest. This is because the innovativeness of suppliers provides buyers with another way of catching up to technological change (innovations made by suppliers do not substitute for internal R&D efforts). Firms have incentives to outsource most components, exploit competitors' technological advances, and concentrate innovation on the remaining few internal components.

This seems to work until we enter in phase II, in which firms compete to define the product standard. The large and frequent emergence in the market of different product definitions induces an abrupt internalisation of most product components. Although suppliers try to keep up with the changing frontier, it is impossible to appropriate the technological gains from an innovation without adjusting all other components coherently within the product architecture. Therefore, there is little scope for intermediate component sales, and firms are forced to chase the technological frontier by adopting an integral strategy.

Once a standard has been defined, competition rests on incremental, albeit frequent, product changes. During this phase (III), markets for intermediate components, become technologically viable, although they are different in nature. The frequent changes, albeit small, force suppliers and assemblers alike to continuously adjust their activities, and there is only little room for any firm to establish longstanding dominance of a market segment. Compared to phase I, there is lower firm concentration and differentiation in either the market for segments or final products (Herfindahl index in figure 4). However, with respect to phase II, during which firms still compete to define a standard, the market concentration increases: the firms that settle in the right technological path since the standard is defined, manage to appropriate major advantages from incremental innovations.

When the product reaches maturity (stage IV) learning and economies of scale become essential to compete on price. Firms reinforce the small advantages they have achieved over competitors, gaining market share at their expense, and further increasing their returns to scale and learning. This induces an increasing pattern of market concentration in the current configuration of the industry (final products and established markets for components). Although at this stage we are not aiming at replicating empirical results, this pattern seems in line with the trajectory observed across industries life cycles.

It is worth noting that the final stage envisaged by the model represents the ideal environment for generating a new radical technology. In fact, large firms serving the existing market(s) with products based on familiar and tested technology, have no incentive to explore new technological routes, whenever they may emerge. However, non–commercial institutions or firms serving other markets will continue to explore the technological landscape. Any potential application of the product in the established market is likely to be initially ignored by incumbents, which, besides lacking any incentives to alter a favourable situation, will have no particular advantages in a technological race against competitors. Assuming that technological opportunities arrive exogenously at a constant rate, a prolonged period during which such opportunities are ignored is likely to produce, eventually, the "sudden" emergence of a new technology, which is actually the result of slow accumulation of small innovations not exploited by uninterested incumbents. While a new product cycle is starting, new firms are likely to enter the market, while some of the incumbent may find themselves too backward with respect to the twists in the technological frontier (Klepper 1997).

5 Concluding remarks

Our work focuses on the relation between organisational behaviour, complex technological innovation and firm competitiveness. We investigated some of the forces determining the "vertical" organisation of markets, i.e., which components (or which parts of the production process) are retained in–house, and which are outsourced. Specifically, we analysed how aggregate industry properties are influenced by the dynamics of aggregate technological progress and firm level competitive behaviour (including product innovation).

The difficulty involved in dealing formally with these issues (difficult to generalise because empirical observation is riddled with highly idiosyncratic specificities and there is little we know about generally observable innovation behaviour which is not highly stochastic) justifies the choice of a simulation model representing a limited set of the activities involved in real world markets. The properties of the model we have discussed provide a consistent perspective within which to interpret empirical observations and to shed light on the rarely considered issue of the joint effect of competitive and technological conditions on determining production structures in competitive markets, compared to decisions of individual firms based purely on cost or technological incentives.

Our results show that different market configurations are likely to emerge in different phases, with different dynamics of technological opportunities. In this respect, the distance between the firm technological advance and the frontier of technological opportunities play a relevant role, but is by no means a sufficient explanation. The results also show that there is no negative (and monotonic) relation between the speed of technological change and the degree of integration of an industry, and that during a product life cycle, we can expect successive waves of integration and disintegration of the production structure. Within the rather strict limitations of our model, we can also point to some of the motivations for firms' decisions about the (market) extensions to production activities. We derive systemic properties of an industry pointing to an explanation for the decentralised behaviour of its firms.

Because the issue discussed in this work is at the core of industrial dynamics, and the simulation model we have developed can be easily replicated and modified, we believe that our work can be extended in many relevant directions. The model could include several additional aspects and endogenise elements currently assumed to be exogenous. For example, this model could be used to investigate the more extensively studied 'horizontal' organisation of markets, i.e. the reason for a given distributions of market shares and dynamics. We deliberately underplayed the results of the model in terms of market distribution, since we believe that this aspect is heavily influenced by the forces governing market entry and exit of firms, which the current version of our model does not take account of.

Another interesting research direction would be to apply the model to investigating the endogenous development of new markets, sub-markets and niches, resulting from the interplay between technological development and demand characteristics. This is an issue that is attracting increasing research interest (Klepper and Thompson 2006), and could exploit the current representation of a technological landscape, which is sufficiently flexible to allow a large number of configurations; it would require more careful definition of demand, allowing for strongly differentiated preferences among consumers. A straightforward extension would also allow to analyse the endogenous changes in the product modularity and architecture as. Finally, our model could provide interesting insights into the effects on the industry of different intellectual property protection regimes that restrict innovation by means of patent–like mechanisms.

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