J Evol Econ (2015) 25:875–899
DOI 10.1007/s00191-015-0422-8

REGULAR ARTICLE

“…then came Cisco, and the rest is history”: a ‘history friendly’ model of the Local Area Networking industry

Roberto Fontana [1,2] **· Lorenzo Zirulia** [2,3,4]

Published online: 10 September 2015

Abstract We study the role that switching costs, compatibility, and mergers and acquisitions play in influencing the evolution of a multi-market industry. By looking at the case of the Local Area Networking industry, we propose a ‘history friendly model’ to replicate its evolution during the 1990s. Our model explains how a firm can start from a dominant position in one of the existing markets and exploit switching costs and compatibility to enter a new market. Mergers and acquisitions also play an important role as the new market is pioneered by a start-up, which is soon acquired by the dominant incumbent. As a result of the acquisition, the acquiring firm becomes the leader also in the new market.

Keywords Simulation · History friendly models · Switching costs · Compatibility

JEL Classification D22 · G34 · O30 · L10 · L63

1 Introduction

In this paper we propose a ‘history friendly’ model of the Local Area Networking (LAN) industry in the 1990s. LANs are physical infrastructures enabling computers,

Electronic supplementary material The online version of this article (doi:10.1007/s00191-015-0422-8) contains supplementary material, which is available to authorized users.

✉ Roberto Fontana
roberto.fontana@unibocconi.it

Lorenzo Zirulia
lorenzo.zirulia@unibo.it

1 Department of Economics & Management, University of Pavia, Via San Felice 5, 27100 Pavia, Italy

2 CRIOS - Bocconi University, Via Sarfatti 25, 20139 Milan, Italy

3 Department of Economics, University of Bologna, Bologna, Italy

4 RCEA, Rimini, Italy

peripherals and more in general ‘end stations’ to be linked to form a network connecting different users within an area of narrow extension (i.e., a university campus or different buildings at a company site). The LAN industry is part of the data communication industry. During the 1990s, the period under investigation in this paper, spending in data communication accounted for 30 % of the total spending on communication equipment (Doms 2003). Within the same period, spending on LAN equipment accounted for 47 % of the total for data communications and 14 % of the total for telecommunication equipment in the US (Doms 2003).

‘History friendly’ models (HFMs from now on) are conceived as part of a second generation of evolutionary models of industry evolution. While first generation models (Nelson and Winter 1982) were abstract, general, and primarily aimed at exploring the logic of evolutionary economic processes and at showing the advantages of this new approach, HFMs focus on and explain the historical evolution of specific industries. The first example of a HFM was proposed by Malerba et al. (1999), who also provided a discussion of the HFM methodology.[1] From a substantive point of view, HFMs are motivated by the recognition that any explanation of structural evolution of industries is almost by definition industry-specific, relying on the details of the sectoral system of innovation and production under examination (Malerba and Orsenigo 1996; Malerba 2002). The most common way to analyze the structural evolution is through appreciative theorizing, which consists of a non-formalized explanation of observed phenomena based on specific causal links proposed by the researcher (Nelson and Winter 1982). Although appreciative theorizing must be seen as ‘true’ causal theory and a fundamental process of building a theory, it can be difficult to test if the suggested causal arguments are consistent and sufficient to provide an explanation, in particular, if the phenomena under investigation embody non-linear and path-dependent processes. Malerba et al. (1999) argue that the primary goal of HFMs should be to verify the logical consistency of appreciative theorizing put forth by analysts of the history of an industry or a technology. Therefore, a first objective of the HFM exercise is to assess whether the proposed chain of causal links, together with a set of ‘reasonable’ values for the parameters, is able to replicate the actual evolution of the industry, achieving what Malerba et al. (1999) have defined as ‘history-replicating runs’. If that is the case, the capacity of the formal model, and indirectly of the appreciative theorizing, is supported as a valid explanation of the empirical evidence. After achieving this aim, the model can then be used to perform counterfactual analysis in order to look for what Malerba et al. (1999) called the ‘history-divergent runs’.

Our paper focuses on the structural dynamics and evolution of the LAN industry during the 1990s, an extremely dynamic period in which growth occurred as the consequence of the interplay between technical change and new market creation. The evolution of the LAN industry proceeded in phases, each characterized by the presence of several markets (one for each piece of LAN equipment) and the presence of a ‘focal’ market. During the 1990’s, Cisco Systems was able to become the dominant firm in the LAN industry by extending its dominance from an existing market (routers) into a new market (switches).

[1] Malerba et al.(1999) presents a model of the evolution of the computer industry. Other sectors that have been studied using this approach include pharmaceuticals and biotechnology (Malerba and Orsenigo 2002), and the DRAM industry (Kim and Lee 2003).

The appreciative theory we propose to explain this pattern is based on three elements: switching costs, compatibility, and mergers and acquisitions (M&As). In the LAN industry, switching costs derived mainly from the need to purchase equipment that was compatible with the existing installed base, and from the extra cost customers incurred to learn how to use equipment purchased from different manufacturers. LAN equipment 'work together' on the basis of common and open standards (Jain 2012). However, all the major industry leaders developed families of equipment and dedicated software platforms in an attempt to differentiate their offer from those of competitors (Gawer and Cusumano 2002). In this context, compatibility (or lack thereof) became an important issue to maintain market leadership. M&As of new start-ups where also used by incumbents to restrain competition and to gain access to new technological capabilities. In a nutshell, we argue that Cisco Systems was able to become the industry leader by leveraging its installed base of users, through switching costs and compatibility, while simultaneously acquiring new technological capabilities through a mix of targeted M&As (Mayer and Kenney 2004).

Our formal model captures all the distinguishing features of this appreciative theory, and it produces results that are in line with the observed history. In particular, the observed high level of concentration and a high market share for the leader in all the markets is obtained only for a positive level of switching costs. M&As also play a crucial role in shaping the industry evolution, so excluding them produces an evolution of the industry that is rather different from the observed one.

Alongside the contribution of our modelling exercise, our work contributes to a recent stream of literature that studies the co-evolutionary dynamics of related markets (Malerba et al. 2008; Malerba and Orsenigo 2010; Bhaskarabhatla and Klepper 2014). We extend this literature by considering the case of co-evolution of markets for complementary goods in the presence of 'frictions' such as switching costs and partial compatibility. So called 'platform based industries' present similar characteristics, and some of the dynamics we describe are likely to be observed also in these industries.

The paper is structured as follows. Section 2 provides the background information on the evolution of the LAN industry. In particular, it identifies those facts of industry evolution upon which we intend to focus, and sets the stage for the development of an appreciative theory in Section 3. Section 4 describes the HFM. Section 5 reports the results from numerical simulations and presents first history-replicating runs, followed by few history-divergent runs. Section 6 concludes by discussing the findings in terms of their contribution to the recent literature on industry evolution.

2 The evolution of the LAN industry

2.1 Overview and definitions

LANs are the physical infrastructure enabling data communication across an area of narrow extension (e.g., a university or company). Over LANs data travel in packets from a sender to a data receiver according to 'rules' defined by standards. The infrastructure of modern LANs is made up of several types of equipment that govern the data traffic at different levels of technological complexity and hierarchy.

We focus on three types of equipment: hubs, routers, and switches. Within a LAN, each piece of equipment plays a specific role. Hubs are very simple equipment used to extend networks. Routers are technologically complex, as they embody the algorithms used to transfer data optimally across users and between separate LANs. Switches are used to accelerate data transfer and processing; they are located between hubs and routers in terms of technological complexity. The wiring of hubs, routers, and switches forms a 'system'. LAN firms manufacture and commercialize the pieces of equipment that constitute the system. Each type of equipment is commercialized in a specific market of the industry and LAN manufacturers may or may not be active in every market. During the evolution of the industry, and as a consequence of technological change, the functionality of equipment have changed and the boundaries between the markets have progressively blurred.

The diffusion of office LANs started in the second half of the 1970s. Early LANs were essentially 'company' networks based on proprietary technologies (i.e., the Xerox Network and the DEC Network etc.). An acceleration in the diffusion of LANs within office environments occurred during the first half of the 1980s as a consequence of the endorsement of Ethernet and Token Ring as LAN transmission standards. Both Ethernet and Token Ring enabled companies to connect the sparse existing proprietary LANs by using two types of equipment: bridges and routers. Bridges and routers were mainly used to connect networks running incompatible standards. Hubs were introduced to rationalize cable deployment and enlarge existing networks. At the end of the 1980s, the process of enlargement created congestion problems as new and better performing computers were adopted in company offices and new 'bandwidth hungry' voice and video applications became available. Two possible solutions slowly emerged. The first was the definition of new high speed standards which could enable data packets to travel at higher speed than that provided by Ethernet and Token Ring (10Mbps and 4 Mbps respectively) (Fontana 2008). The second was the deployment of switch equipment which, embodying many of the functionalities played by hubs, progressively substituted for them within high speed LANs (Christensen et al. 1995). This happened during the second half of the 1990s, a period that witnessed the progressive decline of importance of the role of hubs within LANs and the fast diffusion of switches while the router market stood still. The changes in revenues reported in Fig. 1 below reflect the events just summarized.

We now focus on the dynamics of the two key markets in the 1990s, routers and switches.[2]

2.2 The router market

Starting in 1989, the router market has passed through three phases, each opened up by some kind of technological innovation (either radical or incremental). The introduction of the 'multi-protocol function' was the event that opened up the market and engaged router manufacturers in close competition. The market then entered a diversification phase (1992–1994) in which incumbents started to offer 'scaled down' versions of

[2] Existing contributions have provided detailed evidence on the early history of the industry (von Burg 2001) and on the events that have characterized the most recent period especially concerning the optical networking market of the data communication industry (Carpenter et al. 2003).

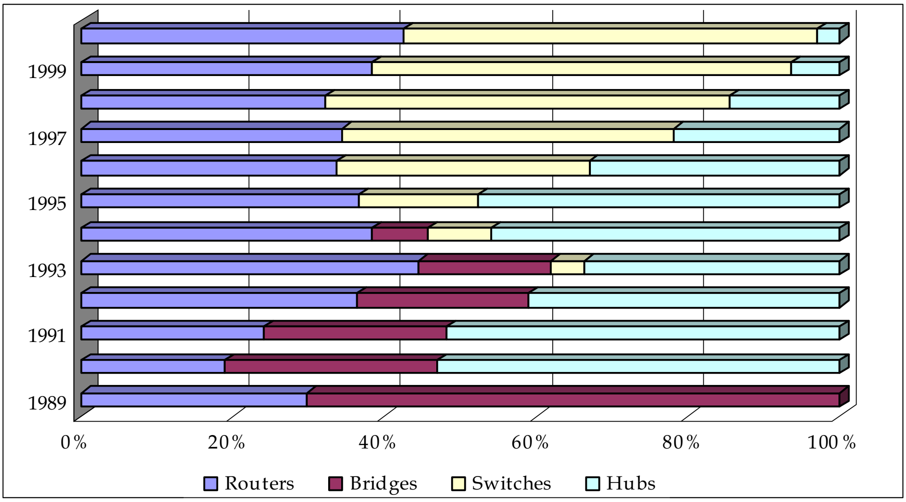

Fig. 1 LAN industry. Revenues by market

previous products, i.e., remote-access routers, following mainly two different innovative strategies, software-only routing and hardware-based routing.[3] A new phase started in 1995 when router manufacturers felt progressively threatened by new entrants coming from the switch market (Miller 1996).

During all these phases, the structure of the router market did not change much. Entry and exit combined with decreasing prices occurred. Market shares and firms' rankings, considering also M&As, remained relatively stable, though a look at the changes in market shares for the overall market between 1990 and 1996 (see Table 1) reveals a tendency toward a growing concentration.

In contrast to this relative stability, there was much more turbulence at the sub-market level (i.e., multi-protocol and remote-access router). During the period of diversification, total revenues in both sub-markets continued to grow and average prices to fall, but at different rates in each sub-market. Prices of multi-protocol routers decreased relatively less than in the remote-access sub-market. Competition was less effective in the case of the multi-protocol sub-market because of higher barriers to entry represented by both the high capabilities required to provide the software responsible for the multi-protocol routing function and the presence of demand side switching costs, due to the introduction of new products that contained proprietary software (Miller 1994).

2.3 The switch market

The first LAN switch was developed in 1990 by a US start-up company: Kalpana. From the technological viewpoint, early switches were an incremental innovation with respect to early bridges that had been previously developed to interconnect LANs using

[3] Multi-protocol routers embody several algorithms and support several communication protocols to deliver data packets intelligently to their destination. Access-routers provide customers with an interface between their end stations and the network.

Table 1 Router market: revenues' market shares

1990		1993		1995		1997	
Vendor	%	Vendor	%	Vendor	%	Vendor	%
Cisco Systems	35.2	Cisco Systems	50	Cisco Systems	48	Cisco Systems	63
DEC	20.3	WellFleet Comm.	16	Bay Networks	17	Bay Networks	10
3Com	13.2	IBM	7	Motorola	6	3Com	4
WellFleet Comm.	8.7	3Com	6	3Com	5	Motorola	3.5
Proteon	7.8	DEC	4	IBM	3	IBM	2.2
Others	14.8	Others	17	Others	21	Others	17.3
TOTAL	100	TOTAL	100	TOTAL	100	TOTAL	100

Source Authors' elaboration based on dell'Oro group reports

different proprietary standards. Thus, when they first appeared on the market, they engaged in a direct competition with bridges rather than with routers. Second generation switches incorporated technological improvements that enabled them to perform more sophisticated data communications, thus challenging what until then had represented exclusive application domains of routers.

The introduction of the LAN switch had a great effect on the structure of the LAN industry. A sign that the new product had fulfilled a latent demand for more bandwidth in the market was an immediate increase in sales aided by falling prices. As a result, in 1997 a typical switch was priced (on average) only 35 % more than a remote-access router. The price premium was even smaller as switches could ensure higher data speed and performance. The commitment of suppliers to address demand came together with a change in firms' revenues and market shares. (See Table 2.)

The arrival of the switch had a profound impact on the sales of the other LAN products. The LAN switch was a definite hit for LAN bridges and sales of routers slowed down. Also, switches represented a window of opportunity for a swarm of new firms to enter the industry, threatening to undermine, for the first time since its foundation, the growth of the router market, and to lay foundations for future changes in the entire industry.

Table 2 Switch market: revenues' market shares

1994		1999 (2 qt)	
Vendor	%	Vendor	%
Kalpana	53	Cisco Systems Inc.	46.7
3Com Corp. (Synernetics)	29	3Com Corp.	13.1
Alantec Corp.	7	Nortel Networks	11.1
Chipcom Corp.	5	Cabletron Systems Inc.	9.8
Lannet	3	IBM	4
Others	3	Others	13.3
TOTAL	100	TOTAL	100

Sources 1994: The Yankee group; 1999: dell'Oro group reports

Concentration levels in the switch market have always been high, though notably lower than in routers. In 1994, the four biggest firms in the market (Cisco Systems (Kalpana), 3Com (Synernetics), Alantec and Chipcom) accounted for 94 % of revenue share. In the 2nd quarter of 1999, the share of the four biggest companies had fallen to 81 %, with Cisco Systems maintaining the lead at 47 %, followed by 3Com, Nortel Networks (Bay Networks) and Cabletron. Contrary to what had happened in the router market where there were no major changes in firms’ rankings, here the market experienced a marked shuffle. This difference is the result of the different dynamics underpinning entry and exit in this market when compared to routers.

Entry in the switch market was driven by three types of manufacturers. First, there were incumbents from within the LAN industry (both from the router and the hub market). Cisco Systems, soon to become the market leader, was originally a router maker and was among the first firms to enter. Second, there were incumbents from outside the industry but with previous experience either in the telecom industry or in the semiconductor industry. Third, there were start-ups searching for new opportunities. After entry, consolidation occurred mainly through a mix of targeted M&As by incumbents. Cisco Systems entered by acquiring Kalpana, the market leader and pioneer of the technology. In 1994, SynOptics (a hub maker) merged with Wellfleet (a pioneer in the router market) to create Bay Networks. Indeed, entry by acquisition soon became one of the main features of the LAN industry and several recent works have investigated both the economic (Fontana and Nesta 2009) and the managerial/organizational (Paulsen 2001; Mayer and Kenney 2004) implications of this growth strategy.

3 Towards an appreciative theory

The previous sections have synthesized the main events and facts that have characterized the structural dynamics and evolution of the LAN industry during the 1990s. The aim of this section is to highlight these facts and to develop an appreciative theory to be formally represented in a HFM.

The first fact emerging from the previous section is that the evolution of the LAN industry proceeded in phases, each characterized by the presence of several markets (one for each LAN product) and by the presence of a ‘focal’ market. The opening up and subsequent growth of the ‘focal’ market was usually the consequence of the interplay between innovation and changes in customers’ needs, which led to the progressive redefinition of the LAN structure through time. In each phase, major firms competed to become dominant in the ‘focal’ market.

The second fact is that dominance was usually achieved through two types of competition. First, there was inter-market competition, which led LAN incumbents to enter into related markets of the industry. This is the competition that occurred along the ‘vertical structure’ of the industry and was facilitated by technological change that made products more and more similar in terms of functions. We define this type of competition as ‘*technological competition*’. Second, there was the competition that occurred within a specific market (i.e., intra-market competition). The aim of this type of competition was to differentiate equipment within each market in order to make the demand increasingly inelastic. We define this type of competition as '*demand competition*'. While technological competition blurred the functional boundaries across products, demand competition led to fragmentation with technological variety that increased both horizontally (i.e., inter-firm market distance grew) and vertically (i.e., the variance of distance from frontier grew as markets became polarized).

The third fact is the role played by new entrants vis-à-vis incumbents in shaping the industry structure. The opening up of a potential 'focal' market triggered a swarm of new entrants, initially start-ups or spin-outs, which could supply new equipment, improve upon an existing one, or compete with incumbents by mean of differentiation first and then price competition. Confronted with the entry of new firms, incumbents reacted in different ways. In particular, a mix of *targeted M&As* was one of the strategies pursued by incumbents to obtain the needed technological capabilities. In the period our model aims to represent, the 1990s, the switch market emerged as the new focal market. Kalpana, a start-up, pioneered the technology and become the market leader; soon, however, it was acquired by Cisco Systems, which was able to extend its dominance from the router into the switch market.

Cisco Systems was by no means the only LAN manufacturer that grew through M&As. What we suggest is that Cisco's M&As' strategy turned out to be successful for the concurrent presence of *switching costs* and *compatibility strategies*. In the LAN industry, switching costs derived mainly from the customers' need to purchase equipment that was compatible with their existing installed base, and from the extra cost of learning to use equipment purchased from different manufacturers. Manufacturers exploited the presence of high switching costs to lock-in customers and to compete against rivals in several ways, for instance, by strategically setting the timing of new product introduction to force customers to buy upgrades. In their analysis of the determinants of switch equipment choice by users, Chen and Forman (2006) present evidence that the presence of an installed base of equipment from a particular manufacturer increases the likelihood of repurchasing from the same vendor if the customer decides to buy again. These issues become particularly important in the case of technologically sophisticated equipment such as high-end switches used in large networks of hundreds or thousands of users, contrasted with low-end switches that were targeted to customers with small networks (Fontana and Nesta 2006).

As far as compatibility is concerned, LANs developed in an environment characterized by open and common standards (Jain 2012; von Burg 2001). In this context, customers in theory could mix-and-match equipment from different manufacturers in the same network. In practice, firms adopted several strategies to 'close' their systems. First, switches need software program to function and manufacturers often designed proprietary software that made their equipment incompatible with that of other manufacturers. For this purpose, Cisco Systems developed the 'Cisco Fusion' architecture first and then the 'Internet Operating Systems' (IOS) software (Gawer and Cusumano 2002).[4] Second, manufacturers introduced families of products that worked well together. These families typically spanned across different categories of users so as to be able to target the entire demand spectrum

[4] In a similar move, Cabletron Systems introduced the 'Spectrum' network management software.

(i.e., going 'end-to-end') and/or to prevent rivals from entering. In 1994, Cisco Systems offered the first product of its Catalyst line of Switch equipment that was enriched in the following years by other high-end as well as low-end equipment.[5]

Both switching costs and compatibility (or lack thereof) provided incumbents a comparative advantage in terms of installed base, to be exploited once technological capabilities were acquired through targeted acquisitions. As an alternative strategy to maintain leadership, incumbents could try *vertical differentiation* (i.e., pushing forward the technological frontier). Since the blurring of functional boundaries across equipment represented a limit to the growth of a specific market, the technological frontier in the specific 'focal' market has to be moved forward for the firm to continue to gain rents. In Table 3, manufacturers are ranked in each market in selected years in terms of their location with respect to the technological frontier.

In the light of the market shares reported in Tables 1 and 2, this evidence suggests that being at the technological frontier was not sufficient as a means to become dominant in the industry. In other words, incumbents were able to maintain their leadership without necessarily competing at the technological frontier. Cisco Systems in both the router and the switch market is the most striking example. This evidence suggests also that new entrants lacked other distinguishing features to challenge the leader: the possibility to leverage upon demand side switching costs and strategies for 'closing its system'.

The formal model we will develop in the next section captures all the essential elements of the appreciative theory outlined above. Innovation takes the form of new product introduction, both within existing markets and in new ones. New products are introduced both by incumbent and new firms. On the demand side, customers incur switching costs when changing suppliers, and products produced by different suppliers may be partially incompatible. Finally, M&As between firms that are complementary in terms of their product portfolio are another distinctive feature of the model.

4 The model

The set-up of the model can be described as follows. Two categories of agents exist: *customers* and *producers*. Customers are firms that buy products (i.e., LAN equipment) to build their system. Producers manufacture and sell the products that constitute a system. Simple rules drive the changes in the product line of manufacturers over time.

4.1 Products

Over the simulation horizon, we consider three types of products, *type 1*, *type 2*, *and type 3*. Each product is described in terms of its quality level ($q>0$). Products are used to build systems. Each system is described by an architecture, which consists in a set of products and weights associated with each product. We consider two possible architectures, *A* and *B*. The quality of the system, which

[5] Again, major competitors did not stand still. 3Com responded with the Superstack and Office Connect line of equipment, the former targeting big users, and the latter customers with smaller networks. Bay Networks and Cabletron Systems marketed an entire new product line: the BayStack and Smartswitch, respectively.

Table 3 Top 5 companies in terms of distance from technological frontier

Routers				
Rank	1993	1995	1997	1999
1	Wellfleet Comm.	Newbridge Networks	Newbridge Networks	Juniper Networks
2	RAD Network Devices	3Com Corp.	Xyplex Whittaker	Cisco Systems
3	Cisco Systems	Network Systems Corp.	Cisco Systems	3Com Corp.
4	ACC	Cray Communications	3Com Corp.	NeoNet-works
5	Andrew Corp.	CrossComm Corp.	Network Systems Corp.	Cabletron Systems
Switches				
Rank	1993	1995	1997	1999
1	Fore Systems Inc.	Newbridge Networks	Newbridge Networks	Cisco Systems
2	DEC	3Com Corp.	Plaintree Systems	3Com Corp.
3	UB Networks Inc.	Hughes LAN Systems	Hughes LAN Systems	Fore Systems Inc.
4	Grand Junction Networks	Cabletron Systems	Optical Data Systems	Lucent Networks.
5	Hewlett-Packard Co.	IBM	Cabletron Systems	Foundry Networks

Sources Predicted prices from hedonic regressions based on author's product database

is determined by the quality of its constituent products and weights, enters into the utility function of customers. Formally, we use y to denote a generic system, and Y to indicate the set of all the systems available at a given moment in time. We denote with $q(y)$ the quality of the system, and $q_k(y)$ the quality of the product of type k in system y.

Architecture A consists of one product of type 1 and one product of type 2. The overall quality of the system can be expressed by a Cobb-Douglas function with weights α and $(1 - \alpha)$:

$$q(y) = (q_1(y))^{\alpha}(q_2(y))^{1-\alpha} \tag{1}$$

Architecture B is constituted of three products, one by each type. In this case, the weights of the Cobb-Douglas function are β_1, β_2 and $1 - \beta_1 - \beta_2$:

$$q(y) = (q_1(y))^{\beta_1}(q_2(y))^{\beta_2}(q_3(y))^{1-\beta_1-\beta_2} \tag{2}$$

At time 0, only architecture A is feasible (i.e., manufacturers cannot produce type 3 products). At time $\bar{t}$ manufacturers can produce type 3 products and therefore architecture B becomes available. Our assumption is that architecture B is better than architecture A, in that it allows reaching quality levels that are impossible to reach under architecture A. Architecture A resembles early LANs in which buyers could combine only two types of equipment (i.e., routers and hubs). Architecture B becomes viable when switches are commercialized. The mechanisms determining products quality are described in Section 4.2.2 below.

4.2 Manufacturers

The number of potentially active manufacturers is exogenously given and fixed at the beginning of the simulation horizon. At the beginning of each period, each manufacturer has a product portfolio made of several products (this portfolio is assumed to be empty at $t=0$). In each period, product portfolios are modified following two simple rules concerning:

1. Mergers and acquisitions;
2. Innovation (i.e., the introduction of new products).

4.2.1 Rules for mergers and acquisitions

At the beginning of each period, M&As may occur according to a two step procedure. In the first step, pairs of potentially merging manufacturers are formed. In the second step, M&As can occur with certain probabilities. To understand how M&As occur, we proceed backward and assume that the pairs of potentially merging manufacturers have been formed. Denote with s_{ki} and s_{kj} manufacturer’s i and j market share (in physical units) in the market for type k product. The probability that the two manufacturers merge is given by:

$$\begin{aligned}
&\text{If } t < \bar{t} \\
&Pr(merger) = 0 \text{ if } \left(s_{ki}-s_{kj}\right) > 0\ \forall\ k \text{ or } \left(s_{kj}-s_{ki}\right) > 0\ \forall\ k \\
&Pr(merger) = \theta\left|\max\left(s_{0i}-s_{0j}, \Delta s_{\min}\right)\right|^{\alpha}\left|\max\left(s_{0i}-s_{0j}, \Delta s_{\min}\right)\right|^{1-\alpha} \text{otherwise.} \\
&\text{If } t \geq \bar{t} \\
&Pr(merger) = 0 \text{ if } \left(s_{ki}-s_{kj}\right) > 0 \forall k \ or\ \left(s_{kj}-s_{ki}\right) > 0 \quad pc\forall k \\
&Pr(merger) = \theta\left|\max\left(s_{0i}-s_{0j}, \Delta s_{\min}\right)\right|^{\beta_1}\left|\max\left(s_{1i}-s_{1j}, \Delta s_{\min}\right)\right|^{\beta_2} \\
&\qquad\left|\max\left(s_{2i}-s_{2j}, \Delta s_{\min}\right)\right|^{1-\beta_1-\beta_2} \quad \text{otherwise}
\end{aligned} \tag{3}$$

where $\theta \geq 0$ and $\Delta s_{\min} > 0$ and ‘small’. The rationale underlying Eq. (3) is that M&As are more likely to occur between manufactures with high shares in different markets. M&As are strategies of external growth, in which firms acquire new technological capabilities ‘embodied’ in products. This is, in fact, the role they played in the LAN industry. $\Delta s_{\min}$ sets a lower bound for positive probability of M&As. In particular, it allows M&As to occur when the relevant architecture is B and manufacturers are not active in all the markets.

To describe how M&As occur in our model, we employ a rule similar to the one adopted by Cowan et al. (2006) to describe the formation of bilateral strategic alliances in a model of knowledge creation. In the first stage, pairs are formed according to the following algorithm. The first pair of manufacturers is given by those manufacturers for which, according to Eq. (3) the probability of merger is the highest. The second pair of manufactures is given by those manufacturers maximizing probability in Eq. (3), *excluding the manufacturers in the first pair*. The third pair is formed by those manufacturers that maximize probability of merging according to Eq. (3), excluding the manufacturers in the first two pairs, and so on.[6]

4.2.2 Rules for innovation

In each simulation period, after M&As have possibly occurred, each manufacturer may change its product portfolio. With an exogenous probability p, the firm introduces a new product.[7] The probability that the product is of a certain type k is:

$$\Pr(type = k) = \frac{\exp(\lambda_1 n_{ik})}{\sum_k \exp(\lambda_1 n_{ik})} \tag{4}$$

where λ_1 is a positive parameter and n_{ik} is the number of products of type k supplied by manufacturer i. According to Eq. (5.4), firms are most likely to innovate in the markets in which they are already most active. This form of cumulativeness can be justified on the basis of idiosyncratic technological competences with specific products. The quality of the new product is drawn with uniform probability in the interval (0, $frontier_k$), where $frontier_k$ is a time invariant technical frontier for product k. We assume that $frontier_3 > max\ (frontier_1, frontier_2)$, which is the reason architecture B (which includes type 3 products) can achieve relatively higher quality levels.

A manufacturer enters a market when it introduces its first product of a specific type. If the manufacturer's product portfolio is initially empty, entry into a specific market coincides with *overall entry*. If the firm is the first one to introduce a product of a certain type, firms' entry also coincides with the opening up of a new market.

4.3 Customers

The number of customer firms is exogenously given and fixed at the beginning of the simulation. In each period, with probability η, each customer is drawn from a distribution to purchase a new system. For simplicity, we assume that, once drawn, a customer simultaneously changes all the products constituting his system. $\overline{q}(y)$ denotes the 'actual quality' of the purchased system. This quality is the one described by Eqs. 1 and 2 only if: (i) the system is composed entirely by products supplied by the same firm or (ii) all products are supplied by firms that do not produce all the products that are feasible in a given moment in time. In all other cases, the 'actual quality' is given by $\overline{q}(y) = \gamma q\ (y)\ \overline{q}(y) = \gamma q\ (y)$, with $\gamma \leq 1$. γ captures the extent of compatibility across

[6] In those cases in which there is a 'tie' (i.e., we observe the same probability of mergers for all pairs in a subset of manufacturers), the first pair is formed by the manufactures with the highest indexes associated to each of them. The second pair is composed by the manufactures with the highest indexes associated to each of them, excluding the manufacturers in the first pair and so on. This 'tie-breaking' rule is adopted to save on computational time. Since ties basically occur when the probability of mergers is 0, the tie-breaking rule is almost irrelevant.

[7] The assumption that p is exogenous may appear too extreme. Indeed, in most evolutionary models it is common practice to assume that the probability to innovate is endogenous and depends (positively) on previous innovativeness, profits or firm size. While this assumption is made for simplifying purposes, we observe that, from a theoretical view point, incentives for product innovation depend less than process innovation on firm size (Cohen and Klepper 1996).

products. The idea is that manufacturers supplying customers with a full line of products can 'close' the system, as happened in the LAN industry through proprietary software. y_{it} identifies the system bought by customer i at time t. y_{it-1} indicates the system bought by the customer in the previous period. The utility customer i benefits from buying y, when he had y_{it-1} in place is described by: [8]

$$U(y_{it}, y_{it\text{-}1}) = D_{it}\overline{q}(y_{it}) - \frac{1}{2}\overline{q}(y_{it})^2 - \sigma_{itt\text{-}1} \tag{5}$$

where σ_{itt-1} denotes a product switching cost equal to $\sigma\chi_{tt-1}$, χ_{tt-1} is the number of products that are present in system y_{it} but not in system y_{it-1}, and σ is a positive parameter. D_{it} is a variable that represents the extent to which a customer is responsive to quality. In particular, it is easy to verify that it corresponds to the 'ideal quality' level for a specific customer, since it corresponds to the quality level that maximizes U. D_i increases over time according to the following expression:

$$D_{it} = D_{i0} + \overline{D}(1 - \exp(-g^*t)) \tag{6}$$

where D_{i0} is uniformly distributed on $[0, \underline{D}]$ and g is a positive parameter. The fact that D_i grows over time is the reason architecture B becomes attractive, first for consumers with high D_{i0} and then to the rest of customers.

The probability that $y_{it} = y$ (i.e., the probability that a customer buys an available system y) is then given by[9]:

$$\Pr(y_{it} = y) = \frac{\exp\left(= (\lambda_2 U(y, y_{it\text{-}1}))\right.}{\sum\limits_{\tilde{y} \in Y} \exp\left(\lambda_2 U\left(\tilde{y}, y_{it\text{-}1}\right)\right)} \tag{7}$$

5 Results

In this section, we report the results from our numerical simulations. Following the HF methodology, we first set out the conditions to obtain history-replication runs (Section 5.1), followed by few history-divergent runs (Section 5.2).

In order to show that our model is able to replicate the observed dynamics, we impose positive switching cost (σ >*0*), partial compatibility (γ <1) and a positive probability for M&As (θ>0). Instead of trying to calibrate σ and γ to an exact value, for each parameter we experiment with a 'low' and a 'high' value. For σ, the values are

[8] This particular utility function borrows from Adner and Levinthal (2001), and many others, the idea that consumers differ in their marginal evaluation of quality. Differently from Adner and Levinthal, however, we do not explicitly consider prices. It can be noted, however, that Eq. (5) can be considered as a reduced form of a case where price is determined by a fixed mark-up over cost, and unit cost of production is quadratic in quality.

[9] The exponential rule for representing consumer choices has been often used in models of industrial and market dynamics (Weisbuch et al. 2000).

1.5 (low switching costs) and 3 (high switching costs). For γ, the values are 0.6 (high compatibility) and 0.2 (low compatibility).[10]

In Section 5.2, we perform two sets of counterfactuals. In the first set, we modify the parameters model. In particular, we look at what happens when the event of switching costs, partial compatibility, and M&As are excluded. Then, we analyze the case of homogenous demand. In the second set, we consider a different mechanism for creating first-mover advantages (i.e., increasing returns), based on supply-side rather than on demand side dynamics.

Table 4 below summarizes the 15 possible scenarios thus created. As for notation, we denote with $Scenario_{(x,\ y,z)}$ the parameter setting in which $\sigma=x$, $\gamma=y$, $\theta=z$, and with $Scenario_{(H)}$ and $Scenario_{(I)}$, respectively, the case of homogenous demand and increasing returns based on supply-side considerations.

Each run lasts 200 periods. Product 3 (i.e., Architecture *B*) becomes feasible at $\bar{t}=100$. For each scenario, we considered 50 runs with different random seeds and looked at the average value (across runs) of a set of indicators (specified below) measured at period 100 (when the new type of product is introduced) and at period 200 (when the run stops). In order to save on space, we will report only what we consider the most important results. We invite the interested reader to look at the Supplementary Material for a full account of all model outcomes.

5.1 History-replicating runs

5.1.1 Results for concentration and market leadership

Table 5 reports the values of the Herfindahl Hirschmann Index (HHI) across markets over time.

Results in columns (1) and (2) summarize the HHI for market 1 at the end of period 100 and at the end of period 200, respectively. It can be noted that, in each scenario, there is a tendency towards greater concentration over time, the level of which is consistent with the observed history. The same dynamics is observed in the second market (columns (3) and (4)).

In economic terms, changes in concentration levels can be understood as the result of interplay of the two types of competition introduced in Section 3: demand and technological competition. On the one hand, *demand competition* tends to lower concentration by providing opportunities for product differentiation. On the other hand, *technological competition* has an opposite (and prevailing) effect, because the opening up of a new market triggers waves of acquisitions, which eventually lead to consolidation.

This general dynamic notwithstanding, differences seem to exist across markets. Theoretically, such differences can be explained by two factors. The first factor is the relative importance of product quality *vis-à-vis* other determinants of customers' choice (switching costs in particular). When choices are mainly taken on the basis of product quality, first mover advantages are limited, competition is intense, and concentration tends to be low. The second factor is the existence of 'unattached'

[10] The values of parameters that remain constant across simulations are reported in the Appendix.

Table 4 Possible Scenarios

History-replicating runs				
		Switching costs	Compatibility	M&As
1	$\text{Scenario}_{(1.5\text{-}0.2\text{-}0.2)}$	Low (σ=1.5)	Low (γ=0.2)	Allowed (θ=0.2)
2	$\text{Scenario}_{(3\text{-}0.2\text{-}0.2)}$	High (σ=3)	Low (γ=0.2)	Allowed (θ=0.2)
3	$\text{Scenario}_{(1.5\text{-}0.6\text{-}0.2)}$	Low (σ=1.5)	High (γ=0.6)	Allowed (θ=0.2)
4	$\text{Scenario}_{(3\text{-}0.6\text{-}0.2)}$	High (σ=3)	High (γ=0.6)	Allowed (θ=0.2)
History-divergent runs				
		Switching costs	Compatibility	M&As
5	$\text{Scenario}_{(1.5\text{-}1\text{-}0.2)}$	Low (σ=1.5)	Full (γ=1)	Allowed (θ=0.2)
6	$\text{Scenario}_{(3\text{-}1\text{-}0.2)}$	High (σ=3)	Full (γ=1)	Allowed (θ=0.2)
7	$\text{Scenario}_{(0\text{-}0.2\text{-}0.2)}$	Null (σ=0)	Low (γ=0.2)	Allowed (θ=0.2)
8	$\text{Scenario}_{(0\text{-}0.6\text{-}0.2)}$	Null (σ=0)	High (γ=0.6)	Allowed (θ=0.2)
9	$\text{Scenario}_{(0\text{-}1\text{-}0.2)}$	Null (σ=0)	Full (γ=1)	Allowed (θ=0.2)
10	$\text{Scenario}_{(1.5\text{-}0.2\text{-}0)}$	Low (σ=1.5)	Low (γ=0.2)	Not Allowed (θ=0)
11	$\text{Scenario}_{(3\text{-}0.2\text{-}0)}$	High (σ=3)	Low (γ=0.2)	Not Allowed (θ=0)
12	$\text{Scenario}_{(1.5\text{-}0.6\text{-}0)}$	Low (σ=1.5)	High (γ=0.6)	Not Allowed (θ=0)
13	$\text{Scenario}_{(3\text{-}0.6\text{-}0)}$	High (σ=3)	High (γ=0.6)	Not Allowed (θ=0)
14	$\text{Scenario}_{(H)}$	Low (σ=1.5)	High (γ=0.6)	Allowed (θ=0.2)
15	$\text{Scenario}_{(I)}$	Null (σ=1.5)	Full (γ=1)	Allowed (θ=0.2)

customers. If 'new' (i.e., not locked into any firm) customers continuously enter the market, 'second mover' manufacturers can cater to them, competition is less intense, and concentration stays relatively low.

We observe that the weight associated with product 2 in determining the overall quality is higher by assumption (0.7 vs. 0.3). This implies that quality is relatively more important than other determinants of choices for market 2 than for market 1, and, therefore, HHIs are usually higher for market 1 than for market 2 for a given scenario. In market 3, customers purchase the product sequentially by entering over time. As a result, competition level stays relatively higher than in the other two markets and HHIs are relatively low. As market 3 should be interpreted as the market for LAN switches, this result is in line with the dynamics described in Section 2.3 above and the figures reported in Table 2.

Table 5 Market concentration (Herfindahl Hirschmann indexes)

	$HHI_{(1\text{-}100)}$	$HHI_{(1\text{-}200)}$	$HHI_{(2\text{-}100)}$	$HHI_{(2\text{-}200)}$	$HHI_{(3\text{-}200)}$
$\text{Scenario}_{(1.5\text{-}0.6\text{-}0.2)}$	0.478	0.605	0.433	0.545	0.339
$\text{Scenario}_{(1.5\text{-}0.2\text{-}0.2)}$	0.430	0.545	0.444	0.554	0.245
$\text{Scenario}_{(3\text{-}0.6\text{-}0.2)}$	0.498	0.636	0.441	0.589	0.338
$\text{Scenario}_{(3\text{-}0.2\text{-}0.2)}$	0.508	0.672	0.480	0.623	0.258

Concerning the effect of switching costs and compatibility on HHI, it can be noted that an increase in the level of switching costs (i.e., high value of σ) leads to a (small) increase in concentration in both market 1 and 2, irrespective of γ. This result follows from a switching-cost-related first mover advantage. By creating frictions in the choices of customers, switching costs tend to favor early innovators *in the market*, and keep concentration levels high. This direct effect is reinforced by M&As that occur when different firms are leaders in different markets and are willing to exploit complementarities. As a result, HHI (slightly) increases.

For given values of switching costs, changes in the degree of compatibility have uneven impacts across markets. In particular, an increase in compatibility (i.e., higher values of γ) has ambiguous (and again small) effects on concentration levels in markets 1 and 2 as it increases concentration in market 1 when switching costs are low and decreases it otherwise. However, it increases concentration in market 3. This is a result that can be explained in terms of the interplay between firms' strategies, demand heterogeneity, and complementarity among products. In order to understand fully the effect of compatibility on concentration, we need to distinguish the case where i) firms tend to produce all the complementary products (which, in the model, occurs when only markets 1 and 2 are open) from the case where ii) some firms, and the leading firms in particular, are specialized (as it is the case for market 3 in the model).

Consider case i). Because of heterogeneous demand, customers will purchase those products that reflect their desired quality. When firms pursue a 'close' strategy, they can increase the appeal of some of their products that otherwise would remain unsold by 'bundling' them together. As a result, demand for these products would increase together with manufacturers' profits. However, pursuing this strategy reduces the extent to what customers can mix and match products. This is likely to reduce demand for other products, which can potentially cater to a larger share of customers. Going into opposite directions, the two effects tend to cancel out. This explains why the concentration level in markets 1 and 2 is not clearly related to changes in the degree of compatibility (γ).

Consider case ii) now. One feature of our model is that start-ups are among the early entrants in the new market. Being first movers, they are likely to exploit their advantage and grow. Incumbents can react to new entrants either by acquiring the new firms (see below) or by 'closing' their system. By reducing compatibility across firms, a 'closed' system strategy allows incumbents to leverage upon their installed base in the other two markets and establish their share in the new one. As a result, the concentration level remains relatively low.[11] This explains why, in market 3, pursuing a 'close' strategy ends up reducing concentration.

To summarize, differences across the scenarios exist. However, these differences are small, which suggest that results (and consequently their 'history-friendliness') are robust with respect to the proposed variations.

[11] The results on the market shares of the leader firm across periods and markets mirror those just discussed for concentration (see Table S1 in Supplementary Material). For a given scenario, the leader's shares increase over time in both markets 1 and 2, while the leader in market 3 has a lower share. The impact of switching cost level and compatibility is the same as in the case of concentration.

5.1.2 Results for industry dominance

It is interesting to understand whether market concentration and leadership in one market is accompanied by leadership in a related market and to what extent this relationship depends on switching costs and compatibility. We report this information in Table 6. In particular, columns (1) and (2) report the frequency of runs in which *a specific firm* achieves the highest shares in every ‘active’ market (i.e., the markets in which at least one unit is sold) after 100 and 200 periods, respectively. This is an indication of the ‘dominance’ of a specific firm in the LAN industry. This frequency can be interpreted as the probability that the real pattern (i.e., dominance) emerges out of the simulation. Columns (3) and (4) report the average (across firms) dispersion in firms’ market shares. Dispersion was computed as the variance of shares across active markets.

Table 6 shows that history replicating runs (in terms of the emergence of dominance) have a significant probability to be observed under all parameter configurations. These results provide further support for the validity of our appreciative theory.

As for the effect of parameters variations on the probability of industry dominance, the following considerations are in order. First and foremost, such probability tends to increase with γ. This result indicates that, for a given level of switching costs, firms pursuing an ‘open system strategy’ are more likely to achieve industry dominance after the new market opens up. This result is more evident for low value of switching costs. At first sight this result is surprising. When firms pursue an open system strategy, customers can easily mix-and-match products in their system and manufacturers are likely to confront a much higher level of competition. As a consequence, we should expect a decline in the market shares and, consequently, a reduction in the probability that one firm achieves industry dominance. However, we first observe that opportunities to ‘mix-and-match’ are beneficial for firms, thanks to a relatively higher level of demand which allows them to grow. As a consequence, if different firms become leaders in different markets, such firms are likely to merge in order to exploit complementarities, and dominance is observed. When the degree of compatibility (γ) is low instead, firms tend to have similar market shares in different markets, and M&As become less attractive.

Second, the effect of switching costs level is generally limited, with the partial exception of low compatibility at period 200 where high switching costs favor the emergence of large firms that end up merging with a positive impact on concentration. Finally, we observe that the above explanations are consistent

Table 6 Industry dominance (frequency) and average market share dispersion

	Dom. t=100	Dom. t=200	Av. Disp. t=100	Av. Disp. t=200
$\text{Scenario}_{(1.5\text{-}0.6\text{-}0.2)}$	0.88	0.76	0.26	0.26
$\text{Scenario}_{(1.5\text{-}0.2\text{-}0.2)}$	0.80	0.54	0.27	0.33
$\text{Scenario}_{(3\text{-}0.6\text{-}0.2)}$	0.76	0.76	0.37	0.23
$\text{Scenario}_{(3\text{-}0.2\text{-}0.2)}$	0.76	0.68	0.35	0.39

with the values of the average dispersion index, where the higher the index, the more dissimilar tend to be the firms' shares across markets.[12]

5.2 History-divergent runs

In accordance with the methodology of HFMs, we now consider possible counterfactuals. Counterfactual analysis is frequently used by social scientists to falsify some antecedents in order to investigate the consequences. In economic history, a pioneer in the use of this method was Fogel (1964), who tried to imagine the conditions of the U.S. economy in 1890 absent railroads. In their discussion on the use of counterfactuals as an empirical tool for evolutionary economics, Cowan and Foray (2002) identify two particular uses of counterfactual put forth in the literature. The first view (Lewis 1973) sees counterfactuals as propositions related to 'worlds' that, although possible, are different from the one that actually exists. The second view (Elster 1978), understands history as a tree in which each decision represents a branching point, leading to new decisions and new branching points as time elapses. In this case, performing counterfactual analysis means 'moving backwards' in the decision tree and taking a different decision, leading to a different branch, at some point. This view is somewhat more appealing, or at least intriguing, for scholars in the evolutionary tradition, for which path-dependence and the role of history in the selection of trajectories (if not equilibria) is important. At the same time, though, this approach poses more subtle issues on the validity of the exercise in terms of the ancillary assumptions one needs to make.[13]

In the HFM tradition, we find examples of counterfactuals that are consistent with both views.[14] In this paper, however, we exclusively consider counterfactuals of the former type. Specifically, by assuming out switching costs, partial compatibility, and M&As we obtain history-divergent outcomes within the same system of causal links. Moreover, we also experiment with other mechanisms for industrial evolution, in particular related to increasing returns on the supply side. We find that these mechanisms alone can explain some facts of industry evolution, but not all of them.

Our first counterfactual aims at disentangling the relative importance of the different mechanisms we identified as important to explain the industry evolution.[15] We start by considering what happens in the absence of switching costs and full compatibility. It turns out that setting switching costs to zero has a very strong impact on industry evolution, leading to truly history-divergent results. Concentration levels in markets 1 and 2 are significantly lower than in our baseline case, even lower than concentration in

[12] We also considered the effect of our scenarios on another set of aspects that are relevant for describing the evolution of the LAN industry, namely: the frequency of runs in which the firm that was the first to introduce a product of type 3 was a start-up; the frequency of runs in which the start-up that pioneered a product of type 3 ends up being acquired and/or merged; the frequency of runs in which the start-up that starts the new market becomes the leader of the market. The detailed results of this exercise are available in Table S2 of the Supplementary Material.

[13] See Cowan and Foray (2002) and Tucker (1999) for a detailed discussion of this point.

[14] Within the 'possible worlds' view of counterfactuals we find exercises of 'comparative dynamics' in which key parameters are varied. Within the 'branching' view of counterfactuals, instead, one can include those experiments trying to verify the effect of specific public policies (which can be located in time) on industrial evolution. See the review of Garavaglia (2010), Section 4.2, for a selection of counterfactual exercises implemented in the literature.

[15] The detailed results of this exercise are presented in Table S3 of the Supplementary Material.

market 3, which goes against the observed evidence. Moreover, dominance is significantly less likely to occur. Full compatibility, on the contrary, has a negligible impact on the results. Our model suggests that firms' strategies to 'close' the systems should combine with firm expertise in order to achieve high market shares and leadership. Indeed, in the absence of strong economies of scope among different products, as is the case in our model, a strategy to 'close' the system *alone* does not provide any comparative advantage, as firms' lack of expertise and capabilities in one market makes the strategy ineffective. This counterfactual further confirms the appreciative theory and highlights the important role played, in particular, by switching costs in reproducing the high level of concentration and the dominance of a single firm. All in all, this result suggests that good calibration (i.e., 'history friendliness') seems to require inclusion of demand side factors such as switching costs.[16]

In the second counterfactual,[17] we explore the extent to what M&As, which we did observe in reality, played a crucial role for the consolidation of the industry into a tight oligopoly. In their case study of Cisco Systems' acquisition strategy, Mayer and Kenney (2004) argued that the development of an 'acquisition and development' strategy was essential for the survival and growth of the company and that acquisitions played an important role in its overall competitive strategy. To gain a better understanding as to whether M&As are crucial *vis-à-vis* other mechanisms we exclude in our counterfactual the possibility to merge. Our first result concerns the concentration levels: apart from cases in which switching costs are high and compatibility is low, concentration is usually lower than in our baseline case. More interestingly, it does not grow when market 3 starts and even decreases in a few cases. The second result is that no dominant firm in the industry seems to emerge at the end of the simulation runs. Both results point to the crucial role played by M&As both in determining the competitive strategy at the firm level, as argued by Mayer and Kenney (2004), and in shaping the industry evolution.[18]

In the third counterfactual[19] we further investigate the role played by demand heterogeneity. In our model, we assume that customers have heterogeneous preferences and that, as a consequence, sub-markets exist within each market corresponding to the specific needs of customer firms. This is what we observed in reality both in the case of routers (i.e., multiprotocol vs. access-routers) and in the case of switches (high-end vs. low-end). To understand the implication of this assumption for industry level dynamics, our counterfactual assumes instead homogenous demand. In particular, in Eq. (6), we fix $D_{i0} = \frac{D}{2}$ for each i. The other parameter values remain set as in $Scenario_{(1.5\text{-}0.6\text{-}0.2)}$. It turns out that results are not substantially affected, although, as happens when switching costs increase, the level of concentration within each market slightly increases.

[16] The importance of switching costs is also confirmed by an experiment (nor reported here) in which, for each firm, the switching cost parameter was positive with probability 0.5, and null otherwise. Out of 100 simulations, it turns out that 97 % of the times a market leader emerges with positive switching costs in market 1, 94 % of the times in market 2, and 67 % of the times in market 3.

[17] See Table S4 of the Supplementary Material.

[18] It must be highlighted that M&As may not be needed if switching costs are high and compatibility low. In this case, first mover advantages (in a market, then extended to others through 'system closure') can be so strong as to lead to dominance without mergers.

[19] See Table S5 of the Supplementary Material.

The final counterfactual, and the one we deem as the most intriguing, is an exploration of an alternative mechanism to create first mover advantages based on persistence in the innovative activity. We abstract from the presence of any demand related mechanism by setting switching costs to zero and imposing full compatibility. At the same time, we impose increasing returns at the market level by modifying the innovation rule according to the following algorithm. First, with probability $p*n$ (where p is fixed at the level of the baseline simulation), there is one innovation. The innovation is given to firm i with probability proportional to $1+n_i^{t-1}$ where n_i^{t-1} is the total number of products (of all types) offered by firm i at t-1. The probability is therefore:

$$\Pr(''i \text{ innovates}'') = \frac{1 + n_i^{t-1}}{\sum_{k=1}^{N} \left(1 + n_k^{t-1}\right)} \tag{8}$$

Once the product is assigned to a firm, the product type is determined as in (4). While there is little and unclear evidence that persistence in product innovation historically played an important role for achieving market leadership in the LAN industry,[20] we think this exercise could indirectly increase the support for our model by ruling out an alternative mechanism, in principle able to account for the industry evolution.

Results, which are reported in Table 7, show that this version of the model is able to reproduce all the observed features of industry evolution, with an exception. In fact, the concentration in market 3 (the switch market in reality) is higher than concentration in markets 1 and 2, which is contrary to what can be observed in the history. The explanation of this counterfactual result is that the increasing return mechanism we impose favors incumbents (in the overall market) *vis-à-vis* new entrants, which have instead more opportunities to gain market share when the source of first-mover advantage is specific to a single market, as in the case of switching costs.

6 Conclusion

This paper has proposed a HFM of the evolution of the LAN industry in the 1990s. Our model embodies some key features of the industry: competition in product innovation with demand heterogeneity, switching costs, the possibility of supplying 'closed systems', the emergence of new markets, and M&As. Our results are able to reproduce some stylized facts of the industry. In the model, as in the 'real world', we observe a tendency towards the creation of a dominating firm (Cisco Systems in this case). This firm starts from a dominant position in one of the existing markets (i.e., routers) and reinforces its position when a new market (i.e., switches) emerges. The new market is pioneered by a new start-up (Kalpana in this case), which is soon acquired by the

[20] Fontana and Vezzulli (2015) show that technological leaders in the LAN industry were more likely to be persistent product innovators *in their market*. However, they do not investigate the relationship between innovation persistence and market leadership.

Table 7 Counterfactual: supply-related increasing returns

Scenario$_{(I)}$	HHI$_{(1\text{-}100)}$	HHI$_{(1\text{-}200)}$	HHI$_{(2\text{-}100)}$	HHI$_{(2\text{-}100)}$	HHI$_{(3\text{-}100)}$
	0.266	0.390	0.260	0.395	0.477
	Inn3New	Inn3Leader	Leader$_{(3\text{-}200)}$	Inn3Merge	Dom. t=200
	0.86	1	0.652	0.98	0.66

dominant incumbent (Cisco Systems). As a result of the acquisition, the acquiring firm becomes the leader in the new market as well. Acquisition of new start-ups provides incumbents with the required knowledge to compete in the new market as well as with the necessary products to extend their portfolio. Once entered in the new market, incumbents use their dominant position in other markets to become dominant also in the new one.

Our results, we believe, can provide insights that go beyond the specific case study investigated here. First and foremost, our results contribute to the literature that investigates the conditions under which diversifying entrants may out-perform *de-novo* entrants in an industry (Klepper and Simons 2000; King and Tucci 2002; Klepper 2002). Superior knowledge of both technology and market has been often identified as a fundamental driver (Agarwal et al. 2004) of this performance. Our results add to this literature by explicitly suggesting that mergers may also play an important role for the acquisition of superior technological and market know-how upon entry, especially when the diversifier is the leader in the original market.

A second contribution is to the literature that investigates entry and innovation dynamics within the broader context of related markets (Malerba et al. 2008; Malerba and Orsenigo 2010). Our results show that new entrants can exploit their installed base in a *complementary* market to obtain a superior performance in the new market whenever the possibility for customers to 'mix-and-match' products is somehow constrained. Our model also shows that this performance gain in the new market may feed back into the firm's focal market and strengthen its position there. In addition to that, we show that the evolution of each market is affected by the role that the product has in the system, in terms of importance of product quality *vis-à-vis* other factors. While the co-evolution of vertically related market has been already studied within the HFMs tradition (Malerba et al. 2008), to the best of our knowledge the analysis of the co-evolution of complementary industries (or markets) had not yet been addressed. It can be noted that such a dynamic is also typical of situations of 'divided technological leadership' (Bresnahan and Greenstein 1999) in contexts characterized by the presence of a platform leader and an ecosystem of 'complementors' (Gawer and Cusumano 2002). Within these contexts, our approach can be used to identify the 'boundary conditions' under which a platform leader can foster the growth of the platform, provide an incentive to innovative while maintaining the control of the platform itself. At the same time, our approach can also be used to identify under what conditions a platform 'wannabe' might be able to challenge a leader and eventually dethrone it, as has happened to Microsoft and Netscape in the market of software browsers, or to Research In Motion and Palm in the case market of smartphones/Personal Digital Assistants.

Finally, our results resonate with those of Bhaskarabhatla and Klepper (2014) who argue that, in the laser industry following technological change, the emergence of an 'integrative submarket' contributed to the convergence toward a particular design of the product that catered to the preferences of different types of users (Windrum 2005) and paved the way to the industry shake-out. The main difference is that, while in the case of lasers, the integrative market was an 'old' existing niche, in the LAN case it was a new market (i.e., the one for switches). Our results suggest also that when markets are complementary, concentration can emerge at the industry level even if forces low concentration at the (sub)market level. In this case, entry by acquisition in the 'integrative submarket' (as done by Cisco Systems) might be the best strategy for incumbents to maintain and to extend their leadership.[21]

Our model suffers from a number of limitations. Some of these limitations are common to HFMs. In particular, the methodology has been criticized within the debate on the empirical validation of agent-based models in economics (Fagiolo et al. 2007). The central issue, we believe, concerns the extent to which an in-depth description and simulation of an individual case can be helpful in drawing a generalizable set of conclusions about industrial dynamics. With respect to this criticism, we do agree that the identification problem (i.e., how to choose from several alternative explanations for the same phenomenon) is 'by construction' particularly serious for HFMs, although it is frequent also in other types of agent-based models, where the number of parameter assumptions, and consequently the degrees of freedom, tend to be high. However, if one accepts the view that the structural evolution is both industry-specific and worth of explanation, as we do, then HFMs are in fact the only available alternative to check the validity of the appreciative theory by explicitly spelling out the involved mechanisms and assumptions and therefore verifying the soundness of the economic argument. In addition to this, we think that HFMs and other more general evolutionary models of industry evolution, such as Winter et al. (2003) and Bottazzi et al. (2001) among many others, should be seen as complements rather than substitutes. In fact, the latter typically focuses on the structural dynamics of industries, in the terminology of Malerba and Orsenigo (1996), for which one can indeed assume that what is observed in different sectors are realizations of the same 'real-world data generating process'(Fagiolo et al. 2007). [22]

As for the specific limitations of our model we briefly mention two of them. First of all, innovation is modelled as an exogenous event. While this is a sensible choice on both theoretical and empirical grounds, a more complete treatment would probably require modelling the probability to innovate as a function of the firm's R&D investment, possibly taking into account the spillovers by other firms similarly to what has been done in Silverberg and Verspagen (1994). Also, in our model, switching costs and compatibility were exogenously given. One possibility would be to introduce firm-specific levels of switching costs and compatibility by allowing simple (i.e., myopic) strategic reasoning in the model. Both extensions open avenues for future research.

[21] We also observe that, although the effect is not particularly strong, our results that the presence of demand heterogeneity tends to mitigate market concentration are consistent with some recent works on the dynamics of some industries characterized by the presence of sub-markets and the absence of shake-outs (Klepper and Thompson 2006; Buenstorf and Klepper 2010).

[22] Moreover, based on the original HF exercise, extensions of the model may be used to investigate issues of more general interest. For an example of this strategy, see Garavaglia et al. (2012).

Acknowledgments we have greatly benefited from the comments of the editor and two anonymous referees. Shane Greenstein, the late Steven Klepper, William Lazonick, and Franco Malerba commented on a very early version of this paper. Preliminary versions were also presented at the 2006 Schumpeter Society Conference in Nice, at the October 2008 DIME workshop on 'Demand, Innovation, and Industrial Dynamics' in Milano, and at a seminar at CIRCLE, Lund University in December 2012. The usual disclaimers apply.

Appendix 1

Table 8 Numerical values for invariant parameters

Parameter	Symbol	Value
Max responsivess to quality	$\overline{D}$	0.6
Growth in responsiveness to quality	g	0.01
Min responsivess to qualty	$\underline{D}$	0.3
Probability of changing LAN	μ	0.1
Number of customers	N° customers	1000
Discrimination rate in consumer choice	λ_2	20
Weight of product 1 in architecture A	α	0.3
Weight of product 1 in architecture B	β_1	0.1
Weight of product 2 in architecture B	β_2	0.2
Technological frontier for product 1	$frontier_1$	0.4
Technological frontier for product 2	$frontier_2$	0.4
Technological frontier for product 3	$frontier_3$	1
Probability of innovation	p	0.015
Discrimination rate in product type choice	λ_1	0.3
Propensity to merge	θ	0.2
Min probability of merger	$\Delta s_{\min}$	0.1
Number of manufacturers	N° manufacturers	30

References

Adner R, Levinthal D (2001) Demand heterogeneity and technology evolution: implications for product and process innovation. Manag Sci 47(5):611–628

Agarwal R, Echambadi R, Franco AM, Sarkar MB (2004) Knowledge transfer through inheritance: spin-out generation, development, and survival. Acad Manag J 47(4):501–522

Bhaskarabhatla A, Klepper S (2014) Latent submarket dynamics and industry evolution: lessons from the US laser industry. *Industrial and Corporate Change*, forthcoming

Bottazzi G, Dosi G, Rocchetti G (2001) Modes of knowledge accumulation, entry regimes and patterns of industrial evolution. Ind Corp Chang 10(3):609–638

Bresnahan TF, Greenstein S (1999) Technological competition and the structure of the computer industry. J Ind Econ 1–40

Buenstorf G, Klepper S (2010) Submarket dynamics and innovation: the case of the US tire industry. Ind Corp Chang 19(5):1563–1587

Carpenter M, Lazonick W, O'Sullivan M (2003) The stock market and innovative capability of the new economy: the optical networking industry. Ind Corp Chang 12(5):963–1034

Chen P, Forman C (2006) Can vendors influence switching costs and compatibility in an environment with open standards? MIS Q 30:1–22
Christensen KJ, Haas LC, Noel FE, Strole NC (1995) Local area networks. Evolving from shared to switched access. IBM Syst J 34:347–374
Cohen W, Klepper S (1996) Firm size and the nature of innovation within industries: the case of process and product R&D. Rev Econ Stat 78(2):232–243
Cowan R, Foray D (2002) Evolutionary economics and the counterfactual threat: on the nature and role of counterfactual history as an empirical tool in economics. J Evol Econ 12(5):539–562
Cowan R, Jonard N, Zimmerman JB (2006) Evolving networks of inventors. J Evol Econ 16:155–174
Doms M (2003) Communications equipment: what has happened to prices? Federal Reserve Bank of San Francisco, Working Paper n° 15, June
Elster J (1978) Logic and society: contradictions and possible worlds. Wiley, New York
Fagiolo G, Moneta A, Windrum P (2007) A critical guide to empirical validation of agent-based models in economics: methodologies, procedures, and open problems. Comput Econ 30(3):195–226
Fogel R (1964) Railroads and American economic growth: essays in econometric history. John Hopkins Press, Baltimore
Fontana R (2008) Competing technologies and market dominance: standard 'battles' in the Local Area Networking industry. Ind Corp Chang 17(6):1205–1238
Fontana R, Nesta L (2006) Product entry in a fast growing industry: the LAN switch market. J Evol Econ 16(1-2):45–64
Fontana R, Nesta L (2009) Product innovation and survival in a high-tech industry. Rev Ind Organ 34(4):287–306
Fontana R, and Vezzulli, A. (2015) An empirical study of technological leadership and persistence in product innovation, mimeo
Garavaglia C (2010) Modelling industrial dynamics with "History-friendly" simulations. Struct Chang Econ Dyn 21(4):258–275
Garavaglia C, Malerba F, Orsenigo L, Pezzoni M (2012) Technological regimes and demand structure in the evolution of the pharmaceutical industry. J Evol Econ 22 (4) 4: 677–709
Gawer A, Cusumano M (2002) Platform leadership: how intel, microsoft and Cisco drive industry innovation. Harvard University Press, Boston
Jain S (2012) Pragmatic agency in technology standards setting: the case of Ethernet. Res Policy 41(9):1643–1654
Kim C, Lee K (2003) Innovation, technological regimes and organizational selection in industry evolution: a 'history friendly model' of the DRAM industry. Ind Corp Chang 12(6):1195–1221
King AA, Tucci CL (2002) Incumbent entry into new market niches: the role of experience and managerial choice in the creation of dynamic capabilities. Manag Sci 48(2):171–186
Klepper S (2002) The capabilities of new firms and the evolution of the US automobile industry. Ind Corp Chang 11(4):645–666
Klepper S, Simons KL (2000) Dominance by birthright: entry of prior radio producers and competitive ramifications in the US television receiver industry. Strateg Manag J 21(10-11):997–1016
Klepper S, Thompson P (2006) Submarkets and the evolution of market structure. RAND J Econ 37:861–886
Lewis D (1973) Counterfactuals. B. Blackwell, Oxford
Malerba F (2002) Sectoral systems of innovation and production. Res Policy 31(2):247–264
Malerba F, Orsenigo L (1996) The dynamics and evolution of industries. Ind Corp Chang 5(1):51–87
Malerba F, Orsenigo L (2002) Innovation and market structure in the dynamics of the pharmaceutical industry and biotechnology: towards a history-friendly model. Ind Corp Chang 11(4):667–704
Malerba F, Orsenigo L (2010) User–producer relations, innovation and the evolution of market structures under alternative contractual regimes. Struct Chang Econ Dyn 21(1):26–40
Malerba F, Nelson R, Orsenigo L, Winter S (1999) History friendly models of industry evolution: the computer industry. Ind Corp Chang 1:3–41
Malerba F, Nelson R, Orsenigo L, Winter S (2008) Vertical integration and disintegration of computer firms: a history-friendly model of the coevolution of the computer and semiconductor industries. Ind Corp Chang 17(2):197–231
Mayer D, Kenney M (2004) Economic action does not take place in a vacuum: understanding Cisco's acquisition and development strategy. Ind Innov 11(4):299–325
Miller M (1994) Routers: poised to make the transition. Network World, pp 77–94
Miller M (1996) Routers take new root. Network World, pp 43–50
Nelson R, Winter S (1982) An evolutionary theory of economic change. Harvard University Press, Cambridge, MA.

Paulsen E (2001) Inside Cisco. The real story of sustained M&A growth. Wiley and Sons, New York
Silverberg G, Verspagen B (1994) Learning, innovation and economic growth. A long run model of industrial dynamics. Ind Corp Chang 3:199–224
Tucker A (1999) Historiographical counterfactuals and historical contingency. Hist Theory 38(2):264–276
von Burg U (2001) The triumph of Ethernet. Stanford University Press, Stanford
Weisbuch G, Kirman A, Herreiner D (2000) Market organisation and trading relationships. Econ J 110(463): 411–436
Windrum P (2005) Heterogeneous preferences and new innovation cycles in mature industries: the amateur camera industry 1955–1974. Ind Corp Chang 14:1043–1074
Winter SG, Kaniovski YM, Dosi G (2003) A baseline model of industry evolution. J Evol Econ 13(4):355–383