

Financial architecture and industrial technology: A co-evolutionary model

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Abstract

Empirical evidence points to a relation between the financial architecture of an economy and industrial technology: market-based financial systems support the development of industries where innovation is typically radical whereas incremental innovation thrives in association with bank-based finance. I set-up a model where firms choose between either radical or incremental innovation and access external finance either from markets or from a profit-maximizing monopolist bank. In a static environment where all economic agents make optimal decisions, it is the distribution of the firms' heterogeneous ability for radical innovation and other model parameters that uniquely determine the choices made by the firm population and the banker. I run simulations of a dynamic agent-based version of this model, where agents adapt their behavior through reinforcement learning and bankruptcy provides a selection mechanism, to find that this stylized economy is prone to a lock-in phenomenon that can lead the system into different ecologies of technology and finance for the same starting parameters. This shows that co-evolution plays an important part in explaining the observed relation between financial institutions and technology, an important insight for institutional design and reform.

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1 Introduction

A wealth of factors may be important for understanding how industrial innovation drives technological change in a capitalist economy.¹ Financial institutions have been assigned a central role among these factors in a tradition dating back to Schumpeter's analysis of credit and innovation in capitalist economies.² Whereas neoclassical theory, starting with Modigliani and Miller (1958), initially saw finance as neutral to the investment behavior of the firm, a more recent body of work introduces market imperfections into the analysis to explain and compare the observed variations in financial institutions, see Rybczynski (1984); Mayer (1988). The imperfect markets literature identifies two main types of financial architectures through which firms can access external finance - *market based* and *bank based*. Each type of arrangement is seen a social construct that serves in mitigating specific inefficiencies that arise in the relation between the firm and its creditors. The observed institutional variation is traced back to parameters that capture exogenous conditions, either relating to matters of organization or of technology. Market financed systems rely on arm's length relations between firms and their creditors. This means the identity of the parties involved in a transaction is of little relevance and the conditions of the transaction are upheld by explicit, binding contracts. In bank-based systems the interaction between the industry and the financial sector is based on strong, long enduring relationships that are further away from the neoclassical view of free markets. Contracts can be renegotiated, the financiers may have significant market power and use it in defining the relation to the entrepreneur.

Institutionalized variations in the patterns of credit allocation between economies are also extensively treated by the Varieties of Capitalism theory, Hodgson (1996); Hall and Soskice (2001). Their analysis highlights institutional synergies, including a feedback relation between industry and finance. In industries where innovation is typically radical, firms primarily access external finance through markets, while industries where innovations are incremental are shown to blossom in cooperation with bank-based finance. Dosi (1990) discusses the role of financial institutions in dynamically shaping innovation with particular attention to the behavioral aspects of industrial innovation. In his view, al-

¹Nelson (1993) offers a detailed comparative study of institutional forms and their influence on the specific patterns followed by industrial innovation in economies across the globe.

²Bertocco (2008) provides an excellent review of the relevant subject matter in the Schumpeterian analysis, also putting into perspective recent work on financial intermediation in the imperfect markets school.

locative decisions of financing institutions have an important role in shaping technological change in an environment where the long-term dynamics are driven by boundedly rational behavior of search and exploration by firms. Dosi sees technological change as a process of search that, as it strives for the accomplishment of its goals, continues to generate new opportunities, constantly shaping the environment within which the search is performed. Financial institutions play a crucial role in shaping the search process by encouraging specific types of innovative efforts, with a tradeoff between the *selection* of firms with better innovative capabilities and allowing firms to *learn* from experience how and in what directions to search.

Dosi's work, however insightful, lacks the illustrative support of a formal model of how finance shapes innovation. The present paper proposes a model that shows how, contrary to the results of the imperfect markets literature, the association between financial and innovation systems is far from entirely predetermined by exogenous conditions captured by model parameters. Simulations of an environment where economic agents - firms and a monopolist bank³ - adapt their behavior through reinforcement learning reproduce patterns of innovation and financing choices that follow along the prescriptions of a static model with rational choice and imperfect information: incremental innovation is financed by the bank and radical innovation relies on market finance. However, whether the further or the latter financial-technological association is dominant in the long-run appears to be the result of a lock-in phenomenon. That is, for the same model parameters, either one or the other association can emerge. In this sense, the prevalent institutional arrangement is not always - as the standard approach in the Endogenous Institutions literature⁴ would argue - the more efficient one given natural circumstances or 'primitive forces'.

In the next section, I will survey the relevant literature connected to the institutional variation in finance as well a number of the most influential models of heterogeneous innovation. I will focus on work that explicitly considers the relation between financial architecture and innovation both theoretically and empirically. In Section 3, I use insights from the existing literature to build a simple static model of innovation and financing decisions and characterize firms' and financiers' optimal choices. Section 4 explores this model in an agent-based dynamic environment where change is driven by selection, through death and birth of new firms and by learning on both the industrial and the financial sectors of

³In this sense the model takes a step further from the perspective of Dosi (1990), by also allowing the financial environment to change in response to industrial dynamics.

⁴See for instance Greif and Laitin (2004) and Dari-Mattiacci and Guerriero (2011) for agenda-setting discussions of this emerging literature.

the economy. A final section concludes, discussing possible extensions and commenting on the relevance of this illustrative model for policy-making.

2 Literature Review

The variations in the conditions of credit allocation to firms have been under intensive scrutiny in the main-stream of neoclassical economic research. Rajan and Zingales (2001) and Boot (2000) offer systematic surveys and discussions of most of the relevant literature. At the core of this theory lie the imperfections in credit markets. These imperfections are formally treated as agency problems that stem from informational asymmetries between lenders and borrowers as well as hold-up and soft-budget problems that are caused by contract incompleteness.

Although the nomenclature may vary in the literature, the essential lines of distinction used in the classification of these arrangements support a unified antipodal view of the existing institutional variation. Arm's length finance, also referred to as market finance or transactional finance, is typical of the Anglo-Saxon liberal market driven economic environment and features explicit contracts that stipulate binding cash-flows between lenders and debtors, with strict bankruptcy procedures ensuring the adherence of parties to the prearranged conditions. In arm's length finance, information is public and the concerned economic agents do not hold market power, leading to competitive setting of interest rates. Relationship-based finance is typical of financial systems where the financiers, generally banks, hold a preferential position vis-à-vis the firm. One such position, generally established through a long history of cooperation between the parties, gives the financier access to valuable firm-specific information and possibly power to interfere in the decision-making process of the debtor. Relationship-based finance allows for more flexible arrangements between parties, but the creditors may take a de-facto monopolist position vis-a-vis their clients, the firms. This institutional arrangement is most common for the more heavily regulated market economies of continental Europe and in Japan, where the *Keiratsu*⁵ is the paramount example of tight and exclusive cooperation between finance and industry.

Economists have often relied on country-level examples for illustrative purposes or empirical investigations. Germany, Japan, Italy, France and Spain are often used as

⁵Hoshi et al. (1990) provides a synthetic description of the functioning of the *Keiratsu* industrial structure in Japan, with insightful anecdotal illustrations from corporate life.

examples of relationship-based financial architectures, while the UK and US are used to illustrate economies that typically rely on arm's length finance, see Mayer (1988); Allen and Gale (1995); Hall and Soskice (2001); Tadesse (2006); Dosi (1990); Schmidt et al. (1999). However, this dichotomy is not fully polar: whereas in some economies one institutional arrangement may be more widely prevalent than the other, the two types of financing solutions often co-exist in varying proportions, Thakor (1996); Atanassov et al. (2007); Minetti (2011).

Whereas the variation we observe in the realm of financial institutions can be satisfactorily systematized as above, the complexity of the process of technological change makes it harder to grasp in bi-polar systematization all relevant features of the R&D endeavors that drive technological change in an economy. An early attempt at modeling heterogeneity in innovation can be found in Arrow (1962). He models innovation as a reduction in production costs and the qualitative distinction that makes an innovation 'drastic' or not is based upon whether a cost threshold is reached by the successful innovator allowing them to drive competition out of the market.

More elaborate models, where the risk-return features of qualitatively different innovation endeavors are explicitly considered, include Balcer and Lippman (1984); Doraszelski (2004); Lambertini and Mantovani (2010). This work allows for a finer analysis of the R&D process explaining some of the puzzling observations in the behavior of innovating firms. Further considerations of heterogeneous innovation alternatives in competitive market environments are present in Ali et al. (1993); Lambertini and Mantovani (2010). This allows for a more complete picture where the interdependence between the R&D activities inside the firm is taken into account indirectly through the competition in the product markets.

Analyzing technological change outside of the full-rationality paradigm has been proven a productive alternative in the wake of the influential work of Nelson and Winter (1982). Among others, Adner and Levinthal (2001) formalize product and cost innovations in a competitive market model where firms make heuristic-based decisions. Their work is capable of reproducing a number of stylized facts of the dynamics in the electronics industry. Using an agent-based computational model, Dawid and Reimann (2011) match a number of empirical regularities of product and process innovation in the automotive industry. In Zeppini Rossi and Hommes (2011) firms produce the optimal output given their technology and market structure in each time period, but technological change is driven by boundedly rational choices between innovation and imitation in a dynamic discrete choice

model.

It is important to note that economic literature often uses different terminology for, broadly speaking, the same conceptual distinction based upon a tradeoff between the risk and return of R&D investments. For instance Ali et al. (1993) use the distinction pioneering-incremental, Doraszelski (2004) distinguishes between innovations and improvements. With a slight risk of abusive generalization, one could see this dichotomy also present in the more recent strand of literature on recombinant innovation, Zepini Rossi and van den Bergh (2008); Safarzynska and van den Bergh (2011). However, literature that distinguishes between product and process innovations is not always compatible with the line of distinction, based on a risk-return tradeoff, that is considered central here, (Lambertini and Mantovani (2009, 2010)).

2.1 Models of financial intermediation and entrepreneurial investment

Although not specifically considering the process of technological change, the imperfect markets analysis provides valuable insights for understanding the forces through which financial institutions may shape innovation. These insights stem from the examination of optimizing behavior of entrepreneurs who exploit the risk-return profiles of the projects they undertake using credit contracted under different arrangements. Financiers and the contracts they offer carry (some of the) features of the two institutional arrangements discussed above. This work comes as a critique to the neutral finance perspective: finance *can* play an important role in determining the investment decisions of the firm, Mayer (1988); Rajan and Zingales (2001). For instance, such work emphasizes the ability of relationship finance to offer the advantage of insurance against the inefficient liquidation of projects that had a bad start, but might still be profitable in the future. However, relationship finance may also be conducive to project hold-ups by the financier and rent extraction that dull the appeal of daring projects, distorting decision-making away from the ‘first-best’, Rajan (1992).

When the financier is also a shareholder and can directly interfere in the decisions of the firm - as is often the case in a *Keiratsu* - there is a conflict of interest between ownership and creditors distorting investment away from the optimal level. Weinstein and Yafeh (1998) model such a set-up showing that the bank-controlled firm is led to overinvest and also forced to pay a higher price for credit. Taking a step further in

considering the specific aspects of technological change, Allen and Gale (1999) show the financing advantage of markets over intermediaries when the opinion of capital owners about projects' profitability is highly heterogeneous. Their result relies on a trade-off between saving on the cost of monitoring, which is shared when finance is intermediated, and the ability to 'agree to disagree' of individual market investors. They argue that diversity of opinion regarding the profitability of a project is likely an important feature of investment in new technology. Minetti (2011) explains the conservative investment choices by firms with strong bank ties through a hold-up by the bank of projects in new, radical innovation. In his model, radical innovation is disruptive in the sense that it entails a loss of value for the long-term financier, corresponding to the firm-specific knowledge that the relationship banker has about the old technology used by the firm.

Models where financial architecture emerges endogenously from economic behavior are far less abundant. The work of Baliga and Polak (2004) uses a static agency model to illustrate the emergence of either a strongly monitored or an arm's length financial system as two alternative equilibria of a game that can be virtually reduced to a coordination problem for financiers. Chakraborty and Ray (2007) build a model where financial development and architecture emerge as steady state solutions of a dynamic general equilibrium model. In their model, exogenous technological conditions relating to the capital intensity of the production process and lumpiness of industrial investment have an impact on the type of financial system that emerges driven by entrepreneurs' choices. Under this paradigm, institutions are set-up and prevail based on the optimizing behavior of fully rational agents. As argued above, such behavioral assumptions may not be adequate for modeling the process of endogenous technological change.

2.2 Evidence

Empirical studies identify a clear pattern of the association between industrial innovation and the specifics of credit allocation systems. Hall and Soskice (2001) compare patent data between US and Germany, two countries whose financial architectures are considered archetypes of the arm's length and, respectively, relationship-based systems. They find that German firms are more productive in patents for sectors where innovation is typically incremental (i.e. consumer durables, machinery, transport) relative to other sectors where innovation is considered to be typically radical (i.e. biotechnology, pharmaceuticals, semiconductors and IT). American innovation follows a mirror pattern, see Figure

??.

The methodology of Hall and Soskice (2001) left room for criticism and further analysis. Akkermans et al. (2009) offer a qualified view of these results, showing that a more conservative empirical method cannot support the contention of a nation wide specialization when including more countries in the analysis, but in specific industries there are indeed identifiable patterns that go into the direction initially pointed out by the Varieties of Capitalism school. In terms of objectivity, empirical work regarding the issue can only go as far as the ability of researchers to define different types of innovation (or for that matter, industrial innovation altogether⁶) and label data accordingly.

Building an empirical framework based on Allen and Gale (1999) and Yosha (1995), Tadesse (2006) shows that financial architecture has a heterogeneous impact on industrial innovation in ten manufacturing industries across thirty-four countries. The technological distinction is shifted towards the informational value of the firm's investment choices as proxied by the share of intangible assets held by the firm. The main finding is that, whereas market finance promotes faster growth over all, bank finance provides better support for growth in manufacturing sectors with higher ratios of intangible capital. This result, conduces the author to infer that arm's length financing arrangements provide better incentives for firms to adopt new technology and push further the technological frontier. To complete the picture, bank finance is better at protecting proprietary information and thus supports exploitation of existing knowledge.

This relation between financing sources and innovation also holds at a smaller scale, when the comparisons are made between firms in the same industry sectors within the same country. Atanasov et al. (2007) use a sample of US companies to show that arm's length finance is conducive to more radical innovation and higher subsequent firm value. Minetti (2011) finds support for his model of technological conservativeness of relationship-financed firms in a sample of Italian firms. In both studies, the extent to which an innovation is considered to be radical is measured by patent citation data.

⁶As Nelson (1993) points out, it is often difficult to draw an operational frontier and track the road from scientific advancement through technological progress to industrial innovation in terms of new products and production processes. More so, this relation may be very different across industries: biotechnology is characterized by a very tight relation between basic research in the academia and product implementation, Senker (1996). At the other extreme one can consider the example of LASER technology, that needed nearly half a century from the initial theoretical framework to the first technology patent, and from there another 14 years until its first industrial application as a product.

3 A static model of innovation and finance

In this section I propose and analyze a simple static model of the financing and R&D choices made by firms and the corresponding behavior of a monopolist bank in the vein of the imperfect markets literature. I first consider the optimal choices of firms between R&D projects given that they access external funds either through a market type of transactional agreement or a relationship banking one. I then move on to characterize the price setting behavior of a monopolist relationship bank that competes with a decentralized debt market for its customers.

3.1 Firms

Consider a population of N risk neutral firms, indexed i , that have the opportunity to invest an amount of 1 in a project, P . This can be either a radical project that has the potential to bring about a drastic innovation, D , or an incremental project that only improves existing production technology, I . As in Bhattacharya and Mookherjee (1986), this setting abstracts from R&D features pertaining to different scales and costs of projects, and the size of the initial project investment is normalized to 1. More specifically, the projects are assumed to generate the following expected cash-flows:

$$CF_{D,i} = \begin{cases} A_i & \text{with probability } p_A \\ 0 & \text{with probability } 1 - p_A \end{cases}$$

$$CF_{I,i} = \begin{cases} B & \text{with probability } p_B \\ b & \text{with probability } 1 - p_B \end{cases}$$

Firms are heterogeneous in their ability for radical innovation, A_i , which is a realization of a random variable distributed with density f_A on support $[A^L, A^H]$. I assume that $A^L \geq B$. When successful, the incremental project generates less revenue than the radical one. However, when it fails, although it generates a smaller cash-flow, $b < B$, it still provides the firm a safety net, compared to the radical project, $b > 0$. By a common assumption in economic models of innovation, March (1991); Ali et al. (1993), the incremental project also has a higher probability of success than the radical one, $p_A < p_B$. Thus, when successful, radical innovation is more profitable than incremental innovation, but, at the same time, it involves more risk. In the present setting the higher risk is modeled both by a smaller probability of success and the absence of cash-flows in case of

failure. Following Minetti (2011), the incremental project is technologically embedded: even when unsuccessful investment in it still has some value, b . This can come in the form of some technological progress that could eventually be resold to other firms in the market that use the old technology or just a partial technological advance that only achieves a portion of the monetary rewards of full success. The radical project is an attempt by the firm to surpass the existing technological frontier and explore new potential avenues. If successful it would deliver to the firm considerable profits, A_i . However, the new direction may also turn out to be technically or economically unfeasible and unable to produce any cash flows.

In what follows I will consider the firm chooses the project that has delivers higher expected value given its idiosyncratic abilities, A_i . The effects of financing institutions will manifest by altering the threshold of ability for radical innovation, A_\star , above which it is optimal for the risk-neutral firm to invest in the radical project.

3.1.1 Internal finance

When the firm has enough internal funds to cover its R&D investment, it is not threatened by liquidation and evaluates the projects based on their expected value on top of the market rate. Let V_D^{NL} and V_I^{NL} denote the value of the radical and the incremental project respectively, when there is no threat of liquidation. We then have:

$$V_P^{NL} = E_{P,i} - R, \quad (1)$$

where $E_I = E_{I,i} = \mathbb{E}(CF_{P,i}|P = I)$ and $E_{D,i} = \mathbb{E}(CF_{P,i}|P = D)$ are the expected cash-flows generated by investment in the incremental and radical project respectively. The risk neutral firm then chooses the radical project whenever $V_{D,i}^{NL} > V_I^{NL}$, which defines a threshold radical prowess, A_\star^{NL} , for the radical project to be worthwhile to the firm:

$$A_\star^{NL} \equiv \frac{E_I}{p_A}, \quad (2)$$

with firms having $A_i < A_\star^{NL}$ preferring the incremental project and firms with $A_i > A_\star^{NL}$ investing in the radical project. There would therefore be $F(A_\star^{NL})$ incremental innovators and $1 - F(A_\star^{NL})$ radical innovators. In what follows, I examine how this threshold is affected by external finance.

3.1.2 Market finance

When the firm requires external finance in order to begin projects, the economic value of the outcomes described above changes for the firm. When the firm has to make debt service payments from its proceeds, bankruptcy and asset liquidation become issues to be taken into account. I assume that a firm with outstanding debt repayment obligations and insufficient cash to fulfill them incurs a cost of reorganization $c > 0$, which is paid on top of the outstanding debt. Essentially, what happens is that a firm with insufficient cash to cover its debt will have to sell some of its assets in order to avoid bankruptcy. By a natural assumption this is costly to the firm, as the illiquid assets are worth more inside the firm than on the market. The danger of liquidation then becomes a relevant part of the decision-making process. When financed by markets - with a strict required repayment, contractually fixed and non-renegotiable - the firm may be unable to repay its dues. The value of the projects will then be:

$$V_{P,i}^M = E_{P,i} - R - c_P(R), \quad (3)$$

where $c_P(R)$ is the expected cost of liquidation for a firm financed by arm's length market finance, choosing project $P \in \{I, D\}$:

$$\begin{aligned} c_D(R) &= (1 - p_A) c, \quad \forall R \\ c_I(R) &= \begin{cases} 0 & R \leq b \\ (1 - p_B) c & R > b. \end{cases} \end{aligned} \quad (4)$$

Above and in the entire analysis that follows, I assume liquidation of assets inflicts a fixed cost upon the firm as soon as it has to make payments higher than the amount of cash generated by the project it invested in. In case of the radical project, this cost is incurred with probability $1 - p_A$ whenever the project fails. A firm that invested in an incremental project does not always incur liquidation costs when the project fails; it depends on the relationship between the cash flow generated by the project in case of failure and the repayment that the firm has to make, b and respectively R . The difference between expected liquidation costs between the two projects becomes a decision factor for the firm and shifts the threshold level of radical prowess. To simplify notation I define $\Delta c(R) \equiv c_D(R) - c_I(R)$. As firms are risk-neutral, they compare V_D^M to V_I^M and choose the radical project under market finance if their radical prowess A_i is in excess of:

$$A_{\star}^M(R) = \frac{E_I + \Delta c(R)}{p_A}. \quad (5)$$

Since $\Delta c(R) > 0$ the firms become more conservative in their R&D decisions (i.e. the threshold for choosing the radical project is higher) compared to the no-liquidation choice in (2). That is because failure and the subsequent cost of liquidating assets leads to a higher loss of value to the firm when its project fails and it cannot repay its dues. Also the threshold discontinuously depends on the value of the market interest R as implied by the term $\Delta c(R)$ that discontinuously depends on R by the expression in (4), jumping from $(1 - p_A)c$ to $(p_B - p_A)c$ as R becomes greater than b .

To have a meaningful economic problem I impose that the incremental project be economically viable, in expectation, even when the market rate is higher than the project's return in case of failure. That would amount to having $E_I \geq R + (1 - p_B)c$.

3.1.3 Bank finance

In a broad survey paper on financial architecture where its relation to industrial R&D in an economy is also discussed at length, Rajan and Zingales (2001) stress the advantage of relationship banking in mitigating intertemporal risks faced by the innovative firm. Empirical evidence points out that bank influenced firms pay higher interests on average, Weinstein and Yafeh (1998); Agarwal and Hauswald (2008), but also enjoy more flexibility for repayment in case of financial distress, Mayer (1988); ?. Models where relationship-financiers offer flexible state-contingent contracts to the firm are abundant in the imperfect markets literature, for example Rajan (1992), Thadden (1995), and Bolton and Freixas (2000). Whereas the specifics of such models vary from a focus on an informational advantage for banks to the possibility of contract renegotiation, the essential feature that distinguishes relationship from arm's length finance is an intertemporal shift of debt-service payments. By virtue of sharing a long-term relationship with the firm, bank finance is more flexible, with the possibility to adjust required payments over time, contingent on firm project outcomes: the bank can show leniency to a unsuccessful firm if it can effectively bind the firm to pay more when its projects are successful, extracting rents from firm profits due to its preferential position vis-a-vis the firm.

In a simplified form, I draw on these insights and assume the relationship bank offers firms a state contingent debt contract. When a firm is successful in its R&D endeavors it pays R_H while unsuccessful firms pay R_L with $R_L < R < R_H$. Precisely the manner

in which this menu is set will be treated in the following section. In the analysis here, I only assume $R_L > 0$ - the debt payments are always net transfers from the firm to the financier⁷. I also assume that rates are never set so high as to lead firms into bankruptcy after successful innovation: $R_H \leq B$.

To ease notation, I use $R^B \equiv p_B R_H + (1 - p_B) R_L$ to denote the average interest rate paid by an incremental innovator to the bank and $R^A \equiv p_A R_H + (1 - p_A) R_L$ for the average interest paid by a radical innovator to the bank. Also I denote by $\Delta R \equiv R^B - R^A = (p_B - p_A)(R_H - R_L)$. I introduce one further assumption, $R^A \geq R$. This is based on a rich empirical literature documenting that relationship-finance is typically more expensive to the firm than arm's length credit, Weinstein and Yafeh (1998); Agarwal and Ann Elston (2001); Chirinko and Elston (2006); Agarwal and Hauswald (2008).

The value functions for the two projects now become:

$$V_{D,i}^{Bk} = E_{D,i} - R^A - c_D(R_L) \quad (6)$$

and

$$V_I^{Bk} = E_I - R^B - c_I(R_L). \quad (7)$$

The risk-neutral firm again compares V_D^B and V_I^B and chooses the radical project if $A_i > A_\star^{Bk}$ where

$$A_\star^{Bk}(R_L) = \frac{E_I - \Delta R + \Delta c(R_L)}{p_A} \quad (8)$$

Bank finance has, in principle, the potential to either promote more radical innovation or stifle it (compared to the internal financing case) by pushing the decision threshold downwards or respectively upwards. The threshold is, as expected, is lowered by an increase in the difference in expected interest payments between the incremental and the radical project. Conversely, the threshold rises with the difference in the expected liquidation costs between the radical and the incremental project. The difference in expected liquidation costs is always positive and increases in the parameter c . Much like the threshold in (5), the value of $A_\star^{Bk}(R_L)$ discontinuously depends on the relation between b and R_L .

⁷This condition may seem restrictive. However, it can be justified by introducing into the model debt to third parties such as suppliers. Then the bank would offer imperfect insurance against liquidation: leniency with respect to own claims but not extending further credit to cover the claims of third parties.

The following subsection pursues the comparison between market and bank finance. Table (1) gathers all modeling assumptions and the notation simplifications introduced so far.

3.1.4 Financing and Innovation Decisions

Using the above results from conditions (5) and (8), It is now possible to state under which circumstances market finance supports more radical innovation than bank finance if the financial architecture of the economy is exogenous, that is, if firms cannot choose their preferred type of financing source.

Proposition 1 *Assume financial architecture is exogenous: firms are either financed by a bank or by markets without a choice between the two options. Then:*

- If $R_L < R \leq b$ or $b \leq R_L < R$, then $A_\star^M > A_\star^{Bk}$.
- If $R_L \leq b < R$, then there are two possibilities depending on the relation between $c_I(R)$ and ΔR . If $c_I(R) > \Delta R$, we have $A_\star^M < A_\star^{Bk}$. If $c_I(R) < \Delta R$, we have $A_\star^M > A_\star^{Bk}$.

The proof of Proposition 1 is presented in Appendix A. The simple mechanics behind it is based upon comparing the thresholds for investing in the radical project defined by (5) and (8) depending on the relationship between the market rate, the rate charged by the bank in case of failure of the project and the output of the incremental project in case of failure. When, regardless of its outcome, the incremental project would enable the firm to make debt service payments under either type of finance, $R_L < R \leq b$, market finance lowers this threshold. The same goes for the situation when $b < R_L < R$, that is, when failure in the incremental project pushes the firm into reorganization regardless of the type of finance it relies on. This is simply because the firm is more likely to pay R_H when it chooses the incremental project as the probability of success is, by assumption, higher. In both these cases relationship finance does not provide the extra service of insurance against liquidation. When $R_L \leq b < R$, the two types of financing arrangements have a qualitatively different impact on the decision-making process of the firm: bank-finance provides insurance against liquidation for an incremental innovator whereas market finance does not. In this case, market finance incentivizes more of the firm population to take-up the radical project by lowering the decision threshold, A_\star^M ,

Table 1: Model Assumptions and Notation

Label	Assumption	Meaning	Justification
A1	$A_i \geq B$	Radical innovation is more profitable when successful	Model - innovation heterogeneity
A2	A_i is iid on $[A^L, A^H]$	Radical prowess is randomly distributed in the firm population	Model - firm population heterogeneity
A3	$b > 0$	Incremental innovation provides a safety-net cash-flow	Model - innovation heterogeneity
A4	$p_B > p_A$	Incremental innovation has a higher probability of success (is safer)	Model - innovation heterogeneity
A5	$R_L < R < R_H$	Flexible, success-contingent bank contract The Market offers a fixed rate contract.	Model - finance heterogeneity
A6	$c > 0$	Fixed cost of liquidating assets to pay debt	Model - external financing friction
A7	$R^A \geq R$	Bank finance is more expensive to the firm	Empirical
A8	$E_I \geq R + c_I(R)$	Market finance is a-priori feasible for an incremental innovator	Model - relevance of the analysis
N1	$E_I = p_B B + (1 - p_B) b$	Expected CF incremental innovation	Notation
N2	$E_{D,i} = p_A A_i$	Expected CF radical innovation	Notation
N3	$E_D^L = p_A A^L$	Lowest expected CF radical innovation	Notation
N4	$R^B = p_B R_H + (1 - p_B) R_L$	Expected debt payment by an incremental innovator financed by bank	Notation
N5	$R^A = p_A R_H + (1 - p_A) R_L$	Expected debt payment by a radical innovator under bank finance	Notation
N6	$c_D(R) = (1 - p_A) c$	Expected liquidation cost for a radical innovator	Notation
N7	$c_I(R) = \begin{cases} (1 - p_B) c & R > b \\ 0 & R \leq b \end{cases}$	Expected liquidation cost for a incremental innovator	Notation
N7	$\Delta c(R) = c_D(R) - c_I(R)$	Expected difference in liquidation cost	Notation

below it's level under bank finance, A_{\star}^{Bk} , if and only if $c_I(R) > \Delta R$. The previous inequality compares the expected loss that an incremental innovator can protect against by lending from a bank instead of lending from the market, $c_I(R)$, with the extra cost of external finance that a bank financed firm incurs when innovating incrementally instead of radically, $\Delta R = (p_B - p_A)(R_H - R_L)$. When the first quantity offsets the second, bank finance promotes more incremental innovation than market finance.

In an economy with both bank and market finance available, rational firms are able to compare expected profits from their optimal R&D project choice consistent with each type of finance and therefore select the type of finance that would support them in making the highest profits ex-ante. This choice by the innovating firms determines the demand for each type of finance and is presented in the following proposition:

Proposition 2 *When firms can choose over both innovation projects and financing there is a threshold, $A_{\star}^C \equiv \frac{E_I - (R^B - R) + \Delta c(R_L)}{p_A}$ such that:*

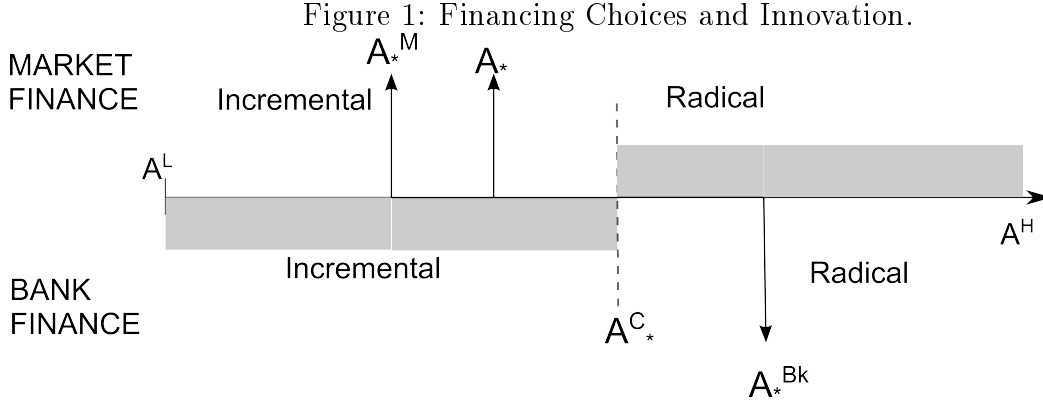
- *All firms with radical ability $A_i < A_{\star}^C$ will be incremental innovators financed by relationship bank credit.*
- *All firms with radical ability $A_i \geq A_{\star}^C$ will be radical innovators financed by market finance.*

Demand for bank finance comes from a fraction $F_A(A_{\star}^C)$ of the firm population and it is positive iff $R_L \leq b < R$ and $R^B < R + c_I(R)$.

One can notice the resemblance between A_{\star}^M , A_{\star}^{Bk} and A_{\star}^C . When the above conditions for positive demand for bank finance are met, we have $A_{\star}^M < A_{\star}^C \leq A_{\star}^{Bk}$ ⁸, meaning that, when firms can also choose their financing source, the decision threshold falls in between the two extreme cases. Some firms that would have been incremental innovators under bank finance have an advantage to become radical innovators financed by the market and some of the firms that would have been radical innovators under market finance prefer to become incremental innovators financed by the bank. The necessity of external funds imposes a distortion in the investment behavior of firms as compared to the 'no-friction' choices described by the threshold A_{\star}^{NL} . When there is a monopolist bank that competes with the market over financing the firm population, this distortion stifles radical innovation by moving the decision threshold upward from what would be the first-best.

⁸When $R < R^A$ the thresholds are strictly ordered: $A_{\star}^M < A_{\star}^C < A_{\star}^{Bk}$.

Figure 1 offers a sketch of the relationship between the thresholds under the conditions of Proposition 2. Notice also that the necessary and sufficient conditions for non-null demand that the bank needs to meet are compatible with the second case of Proposition 1, with market finance supporting more radical innovation than relationship bank finance.



3.2 Financier's Decision

The problem of the banker is to maximize profits by designing a contract, R_L , R_H , for an exogenous market rate, R , and other firm-specific parameters. In order to face non-zero demand for credit the bank must bring about the conditions of Proposition 2 described above. Hence the bank faces the following constraints:

$$R_H \leq B \tag{9}$$

$$R_L \leq b < R, \tag{10}$$

$$R^A \geq R, \tag{11}$$

$$R^B \leq R + c_I(R). \tag{12}$$

Notice that (12) and (10) also imply that market finance supports more radical innovation than bank finance according to Proposition 1. Constraint (9) is based on the natural assumption that the bank does not bankrupt its clients when they succeed. Together with (11) the above conditions are sufficient for non-zero demand for bank credit, in the

context of Proposition 2. According to Proposition 2, all firms that obtain relationship finance from the bank will be incremental innovators. However, whether condition (10) holds or not is not entirely under the control of the bank as the condition also depends the level of the market rate relative to b . I assume that in fact $R > b$, otherwise there would never be any demand for bank finance. A more elaborate argument could be made in a setting where b is allowed to vary between firms, and the analysis above would be restricted only to those relevant firms for which $R > b$. Finally, (11) can be considered as a constraint imposed by capital owners on financial intermediaries engaging in relationship finance. If the relationship supposes some costs associated to monitoring then the bank needs to cover these costs and eventually provide capital owners with at least the same revenues they would obtain through direct, arm's length investment, i.e. buying bonds on the market.

The banker then solves:

$$\max_{R_L, R_H} F(\bar{A}) R^B \quad (13)$$

subject to constraints (9)-(12). This leads to the following proposition:

Proposition 3 *Let $A_\star^C(R^B)$ be the threshold defined in Proposition 2. Depending on model parameters, the optimal menu is either an interior solution defined by the implicit equation:*

$$R^B = p_A \frac{F_A(A_\star^C)}{f(A_\star^C)}.$$

or it is a corner solution with constraint (11) saturated, with the optimal contract given by:

$$R_L = b, R_H = \frac{R - (1 - p_A)b}{p_A}.$$

Essentially, the above proposition describes the financial contract offered through relationship banking as either a rent extracting contract that provides imperfect⁹ insurance against liquidation in return for a higher than market rate expected repayment. When

⁹The insurance is 'imperfect' because it only covers against bankruptcy towards the banker and not against third parties. See also the previous footnote.

this rent-extracting contract is possible, R_H and R_L can be set inside the set defined by constraints (9)-(12), that is $(R_L, R_H) \in \{(0, b] \times (b, B]\}$ as long as the average payment to the bank satisfies $R^B = p_A \frac{F_A(A_\star^C)}{f(A_\star^C)}$ with the requirement that $p_A \frac{F_A(A_\star^C)}{f(A_\star^C)} \leq R + (1 - p_B)c$ to ensure non-null demand for bank credit. When constraint (11) is binding, $R^A = R$, the bank optimally sets R_L equal to its upper bound, b . To satisfy (11) with equality the return in case of success of the project is set to $R_H = \frac{R - (1 - p_A)b}{p_A}$.

The above proposition can be used to obtain a more detailed description of the optimal bank behavior for the case of a uniform distribution of the ability for radical innovation:

Application

Assume radical ability is uniformly distributed on support $[A^L, A^H]$ and denote $E_D^L \equiv p_A A^L$. Then, there is a non-empty parameter space where the optimal menu set by the bank is as follows:

- For $c \geq c^\star$, the bank optimally sets the rent extracting menu as an interior solution:

$$R^B = \frac{R + c_D(R) + E_I - E_D^L}{2}.$$

- When $c < c^\star$, the bank charges interest equal to the market rate, in expectation, through the following menu:

$$R_L = b, R_H = \frac{R - (1 - p_A)b}{p_A}.$$

- The threshold value is given¹⁰ by:

$$c^\star = \frac{2\Delta R + R + E_D^L - E_I}{1 - p_A}$$

The threshold c^\star defines the minimum value of the liquidation cost such that the bank can extract rents by using the interior solution. For low values of the fixed cost of liquidation,

¹⁰This threshold can also be written avoiding the model endogenous ΔR , that is, in terms of the model parameters as $c^\star = \frac{2p_B(R-b) + p_A(2b + E_D^L - E_I - R)}{(1-p_A)p_A}$. This expression can be obtained either by substituting the term ΔR from the expression of the optimal menu when $c < c^\star$, or by imposing $R_L = b$ in the interior solution. That is due to the relation between the interior solution and constraint (11). Since the interior solution only defines the optimal contract as an expected return, the firm can choose any combination of R_H and R_L conforming to it. Given that (11) has a different slope than the isoprofit line in this space, with $1 - p_A > 1 - p_B$, the constraint gradually reduces the set where the interior solution is possible until, for $c = c^\star$, the two solutions coincide, having $R_L = b$.

the bank has to set a contract that brings, on average, the same returns as the arm's length contract traded on the market. When liquidation costs are sufficiently high, the bank can extract rents from its relationship with the firm. Within the parameter space that defines the solution outlined above, It is easy to examine some comparative statics for c^* . Not surprisingly, c^* increases with the attractiveness of the radical project, as reflected by E_D^L and decreases with the attractiveness of the incremental project E_I . Since, according to Proposition 2, there is a one-to-one correspondence between finance and innovation, an increase in the attractiveness of the incremental project makes it easier for the bank to extract rents. However we also have a counter-intuitive result with the positive relation between c^* and R . This is due to the fact that, in our model, the bank cannot make, on average, lower returns than the market. An increase in the market rate is also passed through to the bank rates, so the firms have no extra incentive to switch from market financed radical innovation to bank financed incremental innovation. In relative terms, this makes the advantage of insurance against liquidation offered by the bank less important to the firm and thus pushes c^* upward.

The assumption of a uniform distribution for the radical prowess allows us to precisely and exhaustively define the parameter restrictions required for characterizing the optimal credit contract offered by the fully rational bank. These restrictions are listed in Appendix A and define a non-empty parameter space where the solution has the above structure, which is useful in setting-up the computational exercise presented in the following section.

4 Dynamic features in an Agent-Based framework

Computational methods and agent based modeling have a long-standing tradition in the technological change literature, Nelson and Winter (1982). Dawid (2006) provides a review of agent based models of innovation and technological change. Fagiolo and Dosi (2003) use an agent-based model to investigate the technological microfoundations of macroeconomic fluctuations in an ecology where firms switch between exploitative and exploratory innovative behavior. Dawid and Reimann (2011) use an agent based model to capture features of product and process innovation in the German car industry. In this line, I cast the model presented in the previous section in a agent-based dynamic set-up in order to show that adaptive behavior on the side of both firms and the bank can explain, to a great extent, the patterns in the institutional and industrial variation discussed in the introduction.

The model in the previous section offers a static view of an economy where firms choose their financing sources and R&D strategies rationally, having full information of the available options and the specifics of the innovation process. Likewise, the monopolist bank also has full knowledge of the firm decision process and acts accordingly in setting interest rates and the conditions of the loan contract. In the present section I consider a boundedly rational version of the above model where decisions are at first made randomly and subsequently the agents learn from the outcomes of their past actions. Reinforcement learning is one simple yet effective method to model such dynamics, with relatively good support from experimental evidence. Mookherjee and Sopher (1997) and Erev and Roth (1998) provide the two specifications of the learning process most widely used in the economics literature and show that reinforcement learning models provide the best explanation to the behavior of subjects playing non-cooperative games in experiments. In the following, I report the results obtained using the cumulative reinforcement specification shown to be the best predictor of behavior in Erev and Roth (1998). Nevertheless, qualitatively similar results were obtained using the simple time-averaged specification supported by Mookherjee and Sopher (1997).

The main finding of the computational exercise presented in this section is that innovation and financing choices do evolve together in the direction of the association put forward by empirical studies. In our simulated economy, firms eventually learn to be either radical innovators accessing arm's length finance from the market or incremental innovators that rely on relationship-banking. Moreover, allowing the financial side of the economy to adaptively change the lending contract, gives rise to a lock-in phenomenon. For the same parameter combinations that define the starting conditions, the economy can evolve towards multiple ecologies of financial architecture and technological specialization.

4.1 The set-up

As in the static model of Section 3, there is a single monopolist bank that generates K menus of required returns. Each menu is a contract that specifies the payments that the firm has to make, contingent on its success in the innovation project. In each time period, the bank chooses one menu of the K available, with probability p_t^k . This choice determines the payments for external finance that all firms that have chosen bank finance will make. Probability p_t^k is given in each by the logistic specification of dynamic discrete choice models in the tradition of Brock and Hommes (1997):

$$p_t^k = \frac{\exp(\lambda^B L_t^k)}{\sum_{k=1}^K \exp(\lambda^B L_t^k)}. \quad (14)$$

The reinforcement, L_t^k , of each of the menus available to the banker is given by a discounted time-average of the the profits obtained by the bank from employing a menu, normalized by the size of the firm population. A parameter, δ , discounts past experience by putting exponentially lower weights on profits incurred further in the past. As in Erev and Roth (1998) the reinforcement of menu k accumulates as strategy k is played more often within the bounds imposed by the time discounting parameter, δ . The K menus are generated by combining equally spaced points in the intervals $(0, b)$ for R_L and $[b, B]$ for R_H respectively. For $K = 10$ we have:

$$(R_L, R_H) \in \{(0.20, 1.00); (0.20, 3.00); (0.40, 1.40); (0.40, 2.60); (0.20, 1.00); (0.20, 3.00); (0.40, 1.40); (0.40, 2.60); (0.60, 1.80); (0.60, 2.20); (0.80, 2.20); (0.80, 1.80); (1.00, 2.60); (1.00, 1.40)\} \quad (15)$$

I make this choice in order to cover as uniformly as possible the surface $(0, b] \times [b, B]$ and have at the same time combinations of low R_L with low R_H , low R_L with high R_H and vice-versa. This choice may seem arbitrary, however it is of no particular consequence for our results (see the robustness checks in Subsection 4.3). Essentially, the arbitrary choice of one stable set of menus is required in order to have a setting where initial conditions are always the same between simulations. Otherwise, the results would be confounded between a lock-in phenomenon inherent to the system and the natural product of variation in the model parameters.

A population of N firms, indexed i , each choose one of four finance-innovation strategies $FP \in \{BI, MI, BD, MD\}$ with $F \in \{B, M\}$ accounting for either relationship bank finance or arm's length market finance and innovation $I \in \{I, D\}$, being either the incremental improvement or the drastic advance. Firms are heterogeneous in their ability for radical innovation, A_i , which is drawn from a uniform distribution on support (B, A^H) , but this ability grows with experience in radical innovation by a rate g . This is limited up to the upper bound A^H . Their propensity to choose one of the four combinations of innovation and finance is computed in a manner analogous to the formula of the banker. When the firm generates enough cash-flow to pay its debt the profits increase the firm value under the form of illiquid assets that can be liquidated to cover debt in the future

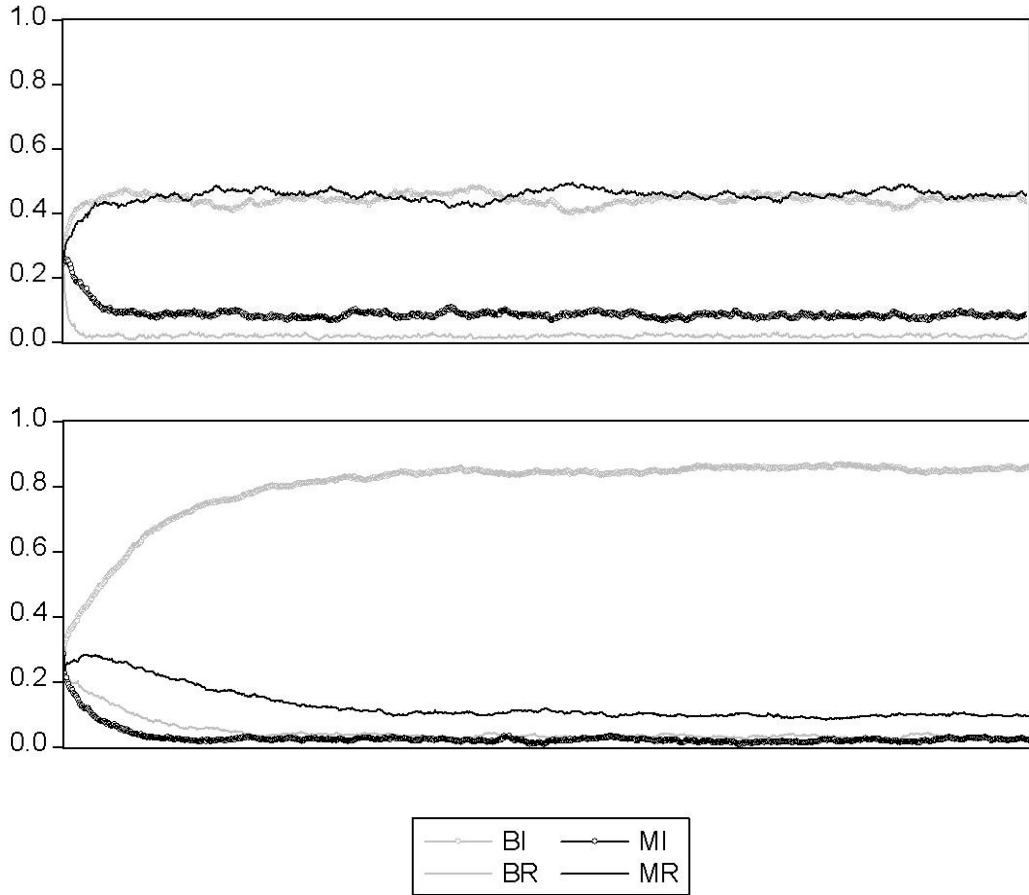
only at the cost c . The value of these illiquid assets depreciates at a constant rate ρ and provides a buffer for the firm against bankruptcy. If this buffer is exhausted the firm dies and is replaced by a new firm with A drawn from the same initialization distribution.

Appendix C contains the detailed dynamic specification of the model.

4.2 Results

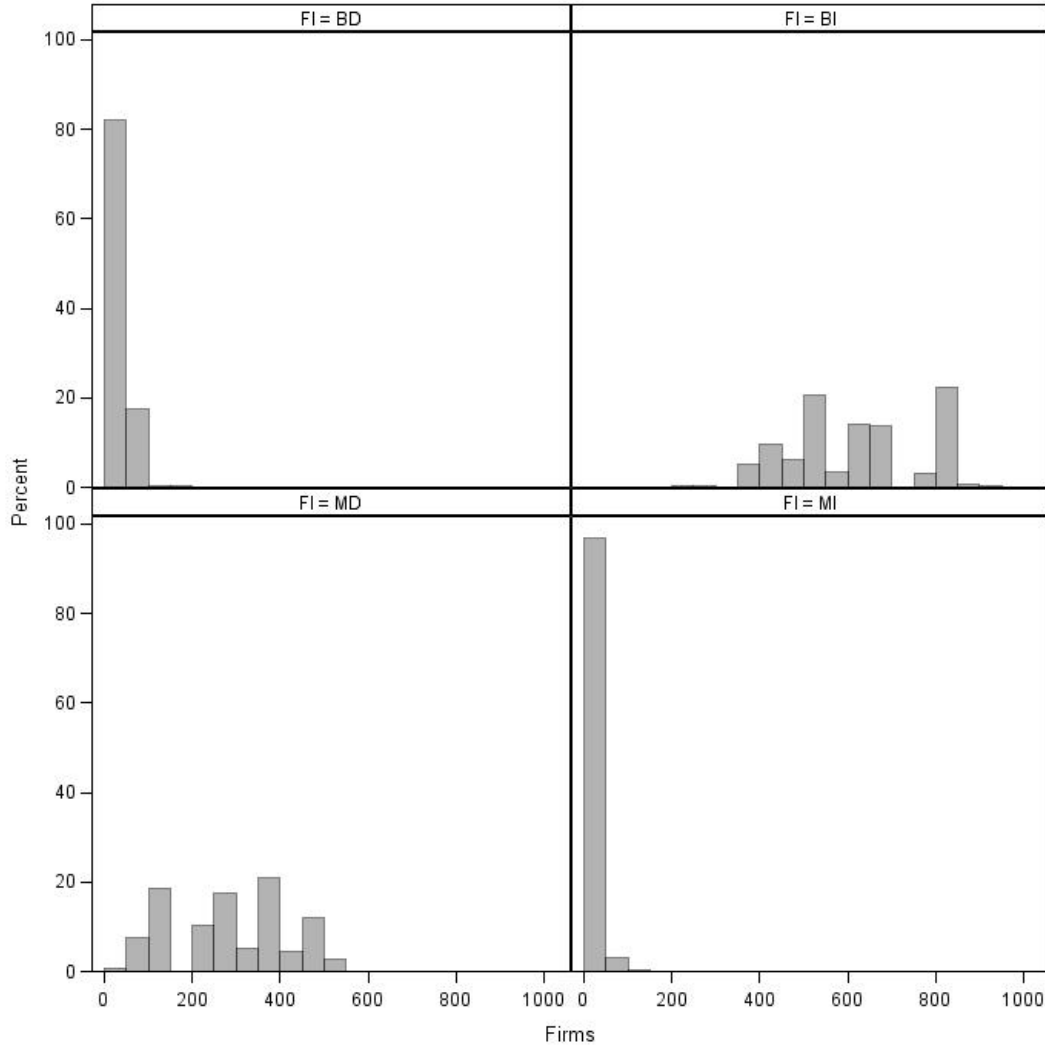
Figure 2 shows the evolution of the system in two simulations, where, for the same model parameters, the economy evolves towards different ecologies of industrial innovation and finance. Radical innovators borrowing from markets can co-exist with incremental innovators borrowing from relationship banking, but the shares in which they do so can vary considerably. Strategies MI and BD are gradually driven out by BI and MD .

Figure 2: Industrial innovation and finance lock-in. $B = 3$, $b = 1$, $A^H = 5$, $c = 8$, $p_A = 0.9$, $p_B = 0.95$, $R = 1.2$, $\delta = 1$, $\lambda = 3$, $K = 10$, $N = 1000$, $T = 20000$



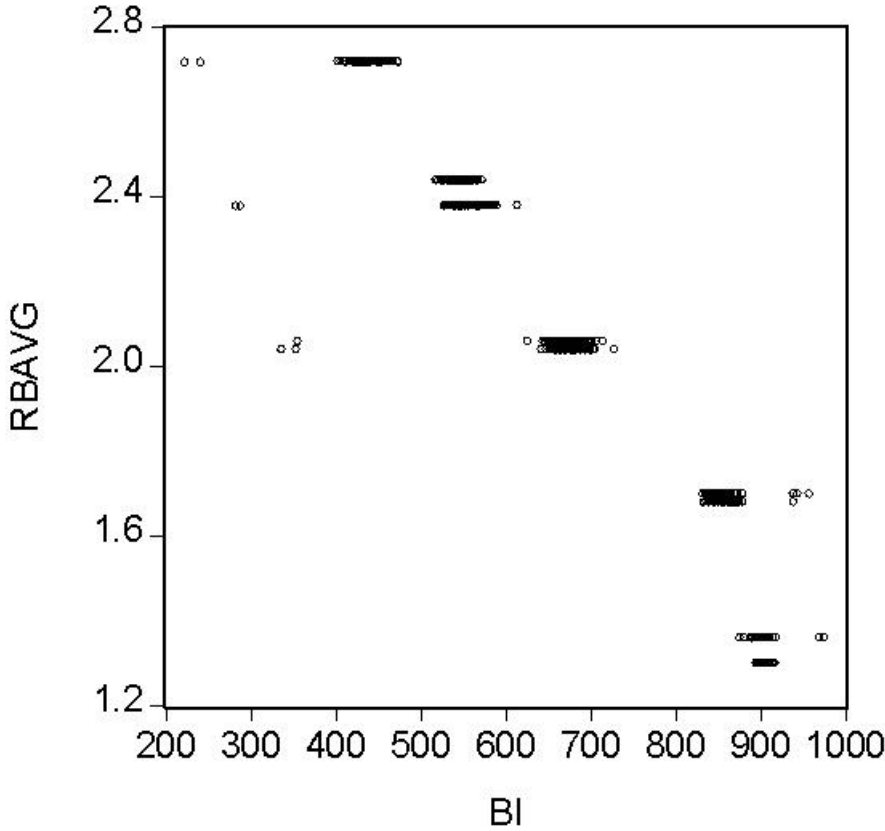
For a more general assessment of the evolution of the economic system, one can create samples of population shares by repeating the simulation for the same start-up parameters. Figure 3 shows the distribution of the final ratio of firm behavior averaged-out over the last 1000 periods of each simulation. The finance-innovation BI and MD associations attract the greater shares of the firm population. Either the system evolves towards a highly relationship-finance dominated economy or to one where both types of finance coexist.

Figure 3: Distribution of final ratios in 1000 simulations. Baseline parameter constellation: $B = 3$, $b = 1$, $A^H = 5$, $g = 1$, $c = 8$, $p_A = 0.9$, $p_B = 0.95$, $R = 1.2$, $\delta = 0.7$, $\lambda^{F/B} = 3$, $K = 10$, $N = 1000$, $T = 20000$. The set of menus generated is the one in (15).



Inspecting Figure 4, one can first see that the bank never converges towards what the optimal menu would be for the parameters considered here. According to Proposition 3, in an environment with rational firms the bank should offer menus that satisfy $R^A = R$, whereas the banker's choices often converge towards menus that are considerably more expensive. As the bank converges to lower priced menus it manages to attract more of the firm population. Still, firms converge to bank finance and pay considerably higher debt service than would be worth on average for the insurance against liquidation that they receive. In explaining this result, selection plays an important role: despite the fact that market financed firms make more profits on average and achieve higher levels of wealth than bank financed firms, the insurance against liquidation offered to incremental innovators by banks makes it impossible for those firms to ever die. Regardless of how much richer market financed firms can become on average, they can still suffer in the very long run a sufficiently persistent series of negative shocks and eventually exit the market.

Figure 4: Final Ratio of BI against average final R^B



Relating to the lock-in phenomenon, one can notice that the firm population ratios also display considerable variation for the same level of final average returns, so the variation in the population shares is not only due to the bank locking onto specific menus.

4.3 Robustness

Figures 5, 6 and 7 examine the effects of variations in the cost of liquidation parameter, c , showing that results remain qualitatively the same for variations of liquidation costs in the vicinity of the baseline setting, where c remains low enough for the bank to be tied to the corner solution according to the results of our application in Section 3¹¹. Not surprisingly, we observe a shift towards more market financed radical innovation when the cost of liquidation is lower. Since the comparative advantage of investing incrementally under bank finance is less important, the *BI* strategy becomes less appealing. However, we cannot say much about what happens in the parameter range where the bank would be able to extract rents: the liquidation costs are so high that all strategies other than *BI* are virtually driven out.

Varying the number of menus offered by the bank, K , Figure 8, and randomizing the set of menus offered by the bank, Figure 9, leads to very little change compared to the results obtained in the baseline case. This provides sufficient reassurance that the lock-in of finance and industry is not an artifact of the arbitrarily chosen set of possible menus, (15), that the bank learns over.

When we consider different degrees of forgetfulness, Figures 10 and 11 the results are qualitatively the same. However we notice a pronounced tendency of the economy to favor the *BI* association when there is less forgetfulness. This is explained by the fact that *BI* can now lock-in faster, whereas all other strategies continue to be trimmed down by selection at the same pace. When forgetfulness is higher, we observe, as expected, a tendency towards more noisy outcomes, that is, the strategies that weren't prevailing in the firm population, *BD* and *MI* become more frequently used.

An inbuilt feature of the Erev and Roth (1998) learning model is the decreasing reaction to new reinforcements as time flows, due to the cumulative specification of reinforcements. Figure 12 explores the properties of the system when initial reinforcements are higher, showing that the results are not qualitatively sensitive to initial reinforcements.

¹¹For the parameter values investigated here $c^* = 10.22$.

5 Conclusion

The above model and its computational investigation is a first attempt at illustrating the co-evolution of industrial innovation and financial institutions when economic agents are boundedly rational and rely on adaptive decision-making heuristics. Moreover, we depict a clear picture of technological and institutional lock-in without relying on the common increasing returns assumption of Arthur (1989).

The model could benefit from several extensions. Whereas the evolution of firms and their choices is driven by learning and selection in the spirit of Dosi (1990), the financing institution evolves only through learning. It would be appropriate to model the dynamics of both finance and the industry on equal grounds. In the spirit of North (1991) and Nelson (2002), this would amount to treating financial institutions as evolving technologies that capital-owners can employ when investing. The model would gain in realism and, most likely, yield stronger results by capturing other features of the financiers' decision making process that may be important in explaining the observed relative technological conservatism of relationship financed firms. While bank finance may have an advantage in terms of monitoring entrepreneurs and directly influencing their choices towards safer R&D projects, markets provide capital owners the advantage of diversification. If market investors enjoy a superior technology for protecting themselves against the losses incurred by the firms they invest in, then it is highly likely that they would be more willing to support higher risk projects that develop new technology.

Furthermore, the modeling of technological evolution could benefit from a richer model that includes the market competition in the industry side. As they are currently modeled, the two innovation alternatives stand as separate sectors, with no within sector competition. A more realistic treatment of industry would require at least within-sector competition. This would serve to highlight a link between the outcomes of research and development activity inside the firm and its effects on the competitors and market organization. A conjecture based on the intuition of some of the extant work is that between-sector R&D competition in the industry would further bolster the emergence of a technological-institutional lock-in phenomenon. When radical innovation is disruptive and cannibalizes the old technology developed through incremental innovation, it is likely that either firms have a stronger incentive to push for radical innovation in order to avoid becoming technological laggards, March (1991), or that centralized finance attempts to stifle the development of new technology in order to preserve a convenient status-quo,

Minetti (2011). Including such features into the analysis would improve the model by empowering it to deliver stronger and clearer results and making it adequate for performing more specific policy analysis. However, the main message of the present work would remain unchanged.

Given the cumbersome specification of the dynamic process, the model does not allow a full analytical description of the dynamics. Hence, results depend on a limited range of parameters. The essential result here is that a very simple model of heterogeneous innovation and heterogeneous finance is sufficient to portray the observed patterns of variation in institutional forms and industrial specialization as the result of a co-evolution of technology and institutions. This view can be seen as a long-term complement to the economic modeling of institutions as arrangements that reduce the cost of frictions that are specific to the economic environments where these institutions prevail. From a long-run perspective, the choices of financiers and firms and the ensuing economic outcomes may be not so much driven by technology-specific exogenous parameters. In this sense, the present work can be seen as a formalization of the insights discussed in Roe (1996) and Greif and Laitin (2004).

The importance of a better understanding of the interaction between technological change and the institutional forms that evolve in an economic system is extensively discussed in Unruh (2000) with a focus on the impact of institutional and technological lock-in on man-induced environmental change. A view of the institutional and technological coordinates of society as, at least partly, the result of reinforced randomness provides a different angle for policy making that deals with institutional improvement and reform. It becomes necessary to understand institutional policy as events that are likely to set the system on new paths of development that may not be trivially anticipated, see for instance Roe (1996) on institutional path-dependence. Conversely, when an institutional form is reinforced by a broad array of technological and organizational complements, a more complete modeling of the inertial forces that would work against change can make for more powerful reform policy, or at least less wasted efforts. Most importantly, if the institutional structures currently in place are, at least in part, the result of chance, then it becomes natural to assume that other, potentially preferable, institutional bundles that have failed to surface in the course of history may be feasible. A formal framework for analyzing the processes of institutional formation and reinforcement is needed as a first step towards creating policy tools adequate for long-term institutional engineering.

Appendix A - Proofs of Propositions

Proposition 1 To say whether **bank finance** supports more or less radical innovation compared to **market finance**, we examine the relationship between the relevant decision thresholds provided by (5) and (8) depending on the relation between b , R and R_L :

- When $R_L < R \leq b$, comparing (5) and (8), bank finance clearly supports more radical innovation as the prowess threshold for choosing radical innovation is lower in (8):

$$E_I + (1 - p_A) c > E_I + (1 - p_A) c - \Delta R$$

- When $R_L \leq b < R$, the threshold in (5) shifts and the one in (8) is as in the previous case. Bank finance supports more radical innovation if the threshold in (8) is lower than the threshold in (5) which happens if and only if:

$$(1 - p_B) c < \Delta R \quad (16)$$

If inequality (16) is reversed, then bank finance supports less radical innovation than market finance.

- When $b < R_L < R$ bank finance always supports more radical innovation than market finance as the prowess threshold for choosing the radical project is again lower:

$$E_I + (p_B - p_A) c > E_I + (p_B - p_A) c - \Delta R \quad (17)$$

Proposition 2 The proof of this proposition comes simply by examining firm profits from R&D projects under each type of finance and then describing their optimal choices case-by-case depending on the relations between the parameters. Formally the firm faces the problem:

$$\max_{FP} \pi^{FP}$$

where

$$\pi^{FP} = \begin{cases} E_I - c_I(R_L) - R^B & FI = BI \\ E_{D,i} - c_D(R_L) - R^A & FI = BD \\ E_I - c_I(R) - R & FI = MI \\ E_{D,i} - c_D(R) - R & FI = MD \end{cases}.$$

At a first glance we can observe that $\pi^{MD} \geq \pi^{BD}$, according to A7 and N6. Assuming the firm chooses market finance when indifferent¹², we exclude BD from the choice set. In order to compare the profits for the remaining alternatives we need to specify the expected liquidation costs in case of the incremental project. This leads to three possible scenarios based on the relation between R , R_L and b :

1. $R_L < R \leq b$:

$$\pi^{FP} = \begin{cases} E_I - R^B & FI = BI \\ E_I - R & FI = MI \\ E_{D,i} - c_D(R) - R & FI = MD \end{cases},$$

in this case, we have $\pi^{MI} > \pi^{BI}$. Hence demand for bank credit will be null, all firms choosing to access market finance. The threshold radical prowess is given by $A_\star^M = \frac{E_I + (1-p_A)c}{p_A}$.

2. $b < R_L < R$:

$$\pi^{FP} = \begin{cases} E_I - R^B - (1-p_B)c & FI = BI \\ E_I - R - (1-p_B)c & FI = MI \\ E_{D,i} - c_D(R) - R & FI = MD \end{cases},$$

in this case, we have $\pi^{MI} > \pi^{BI}$. Hence demand for bank credit will be null, all firms choosing to access market finance. The threshold radical prowess is given by $A_\star^M = \frac{E_I + (p_B - p_A)c}{p_A}$.

3. $R_L \leq b < R$:

$$\pi^{FP} = \begin{cases} E_I - R^B & FI = BI \\ E_I - (1-p_B)c - R & FI = MI \\ E_{D,i} - c_D(R) - R & FI = MD \end{cases},$$

in this case we can have positive demand for bank credit if $\pi^{BI} > \pi^{MI}$ and $\pi^{BI} > \pi^{MD}$ for at least some $A_i \in [A^L, A^H]$. The further inequality amounts to a condition relating model parameters and the expected bank interest: $R^B - R < (1-p_B)c$. The latter inequality defines a new radical prowess threshold, $A_\star^C = \frac{E_I - (R^B - R) + (1-p_A)c}{p_A}$.

¹²Following Baliga and Polak (2004), we assume that, when indifferent, the firm chooses arm's length finance. This could be easily justified by introducing a one time positive cost of initiating a relationship with the financier.

Hence demand for bank finance is positive and comes from firms with $A_i < A_\star^C$ as long as we have $R^B - R < (1 - p_B)c$ and $R_L \leq b < R$.

Under the condition derived above, the entire firm population is split between BI and MD . We can make sure of this by examining the inequality $\pi^{MD} > \pi^{MI}$, such that the firms choose indeed only between MD and BI . we need $A_i > \frac{E_I + (p_B - p_A)c}{p_A} \equiv \tilde{A}$. The threshold, \tilde{A} , which defines the minimum amount of radical prowess such that MD is preferred to MI , is lower than A_C^\star ¹³. Hence MI is preferred to MD only for values of the radical prowess for which BI is preferred to MD . Since BI is always preferred to MI , under the above conditions, the entire firm population is split between BI and MD by the threshold A_\star^C .

Proposition 3 First order conditions for R_L and R_H :

$$\frac{\partial \bar{A}}{\partial R_H} f(A_\star^C) R^B + p_B F(A_\star^C) + \lambda_0 - \lambda_2 p_A + \lambda_3 p_B = 0 \quad (18)$$

$$\frac{\partial \bar{A}}{\partial R_L} f(A_\star^C) R^B + (1 - p_B) F(A_\star^C) + \lambda_1 - \lambda_2 (1 - p_A) + \lambda_3 (1 - p_B) = 0 \quad (19)$$

$$\lambda_0 (B - R_H), \text{ c.s.} \quad (20)$$

$$\lambda_1 (b - R_L) = 0, \text{ c.s.} \quad (21)$$

$$\lambda_2 (R^A - R) = 0, \text{ c.s.} \quad (22)$$

$$\lambda_3 (R + (1 - p_B)c - R^B) = 0, \text{ c.s.} \quad (23)$$

We can add (18) and (19) to obtain:

$$-\frac{1}{p_A} f(A_\star^C) R^B + F(A_\star^C) + \lambda_3 = \lambda_2 - \lambda_1 - \lambda_0 \quad (24)$$

¹³Notice that $R^B - R < (1 - p_B)c \rightarrow \tilde{A} < A_C^\star$.

and this implies:

$$p_B \lambda_1 = \lambda_2 (p_B - p_A) + (1 - p_B) \lambda_0, \quad (25)$$

which, for $p_B > p_A$, helps in eliminating some of the possible solutions that would be inconsistent with the above equality. This excludes

- $\lambda_1 = 0, \lambda_2 = 0, \lambda_0 > 0$;
- $\lambda_1 > 0, \lambda_2 = 0, \lambda_0 = 0$;
- $\lambda_0 = 0; \lambda_1 = 0, \lambda_2 > 0$;
- $\lambda_0 > 0, \lambda_1 = 0, \lambda_2 > 0$.

Based on Proposition 2 we can also point-out that solutions having $\lambda_3 > 0$ lead to null profits for the bank, as demand for bank credit will be zero when (12) is binding.

The above considerations leave the following candidates for optimum:

1. $\lambda_0 = 0; \lambda_1 = 0, \lambda_2 = 0$, and $\lambda_3 = 0$. This implicitly defines a menu R^B that satisfies equation $-\frac{1}{p_A} f_A(A_\star^C) R^B + F_A(A_\star^C) = 0$ (Note that A_\star^C , as defined by Proposition 2, is a function of R^B). Depending on the distribution of radical prowess in the firm population, this solution lies between constraints (12) and (11).
2. $\lambda_0 = 0, \lambda_1 > 0, \lambda_2 > 0$, and $\lambda_3 = 0$. Which gives the solution $R_L = b$ and $R_H = \frac{R - (1 - p_A)b}{p_A}$. This solution satisfies (12) for $c \geq \frac{p_B - p_A}{p_A(1 - p_B)} (R - b)$. For $R_H \leq B$ we need $R - b \leq p_A (B - b)$.
3. $\lambda_0 > 0, \lambda_1 > 0, \lambda_2 > 0$, and $\lambda_3 = 0$ can be part of a solution only for a particular value of the exogenous market rate $R = p_A B + (1 - p_A) b$. This solution is of little interest for the general analysis and also goes against the assumption $E_I \geq R + c_I(R)$.
4. $\lambda_0 > 0; \lambda_1 > 0, \lambda_2 = 0$. This implies $R^B = p_B B + (1 - p_B) b = E_I$. This solution is ruled out by our previous assumption that the incremental project can be viably financed by arm's length finance: $E_I \geq R + c_I(R)$ which is incompatible with constraint 12 for non-zero profits of the firm.

Application

For a uniform distribution of A on support (A^L, A^H) we straightforwardly apply the results of Proposition 3 to find that:

1. There is a closed form for the interior optimum, $R^B = \frac{R+(1-p_A)c+E_I-E_D^L}{2}$. This solution satisfies (12) if $c \geq \underline{c} \equiv \frac{E_I-E_D^L-R}{(1+p_A-2p_B)}$ and (11) if $c > \frac{2\Delta R+R+E_D^L-E_I}{1-p_A}$. Examining the latter inequality, we can conclude that, by setting R_L to its upper bound, b , the bank can exploit the interior solution as long as $c \geq c^* \equiv \frac{2p_B(R-b)+p_A(2b+E_D^L-E_I-R)}{(1-p_A)p_A}$. In order to be possible to construct one such menu with $R^B = \frac{R+(1-p_A)c+E_I-E_D^L}{2}$ that also satisfies $R_H < B$ and $R_L < b$ it is necessary and sufficient to have $E_I > \frac{R+(1-p_A)c+E_I-E_D^L}{2} \leftrightarrow c \leq \bar{c} \equiv \frac{E_I+E_D^L-R}{1-p_A}$.

- For $c^* \leq \bar{c}$, it is necessary to impose $p_B(R-b) \leq p_A(B-b)$.
- For $c^* \geq \underline{c}$, it is sufficient to have $E_I - R \leq E_D^L$ and $1 + p_A - 2p_B \geq 0$.
- For $\underline{c} \leq \bar{c}$, it is necessary that $\frac{p_B-p_A}{1-p_B} [E_I - R] \leq E_D^L$

2. The solution $R_L = b$ and $R_H = \frac{R-(1-p_A)b}{p_A}$ remains the only option for the bank when $c < c^*$.

- For $R_H \leq B$ it is necessary that $R - b \leq p_A(B - b)$.
- For $R^B \leq R + (1 - p_B)c$ We find one of the necessary conditions for non-null demand for bank finance from Proposition 2: $\Delta R \leq (1 - p_B)c$. It can also be stated depending on the model parameters as: $c \geq \frac{p_B-p_A}{p_A(1-p_B)} (R - b)$.

These conditions define a non-empty parameter space for which a solution with the structure as the one above exists. Non-emptiness is easily demonstrated by the parameter choices in the computational exercise of Section 4, which satisfy all of the conditions listed above.

Appendix B

The banker chooses menu k with probability:

$$p_t^k = \frac{\exp(\lambda^B L_t^k)}{\sum_{k=1}^K \exp(\lambda^B L_t^k)}. \quad (26)$$

Following Erev and Roth (1998), the reinforcement of menu k is specified as:

$$L_t^k = \begin{cases} \delta L_{t-1}^k + \pi_{t-1}^k, & k \text{ played} \\ \delta L_{t-1}^k & \text{otherwise} \end{cases} \quad (27)$$

where N_t^k is the number of times menu k has been chosen up to and including period t :

For $N \rightarrow \infty$, the banker's profit from setting menu k is given by:

$$\pi_{t-1}^k = p_{t-1}^{BI} (p_B R_{H,t-1}^k + (1 - p_B) R_{L,t-1}^k) + p_{t-1}^{BR} (p_A R_{H,t-1}^k + (1 - p_A) R_{L,t-1}^k). \quad (28)$$

As long as the firm has positive asset value, $W_{i,t} \geq 0$, its evolution is given by the following equations.

Probability of choosing Finance-Innovation strategy FP :

$$p_t^{FP} = \frac{\exp(\lambda^F L_t^{FP})}{\sum_{FI \in \{BI, MI, BD, MD\}} \exp(\lambda^F L_t^{FP})}. \quad (29)$$

Reinforcement of Finance-Innovation strategy FP :

$$L_{i,t}^{FI} = \begin{cases} \delta L_{t-1}^{FP} + \pi_{t-1}^{FP}, & FP \text{ played} \\ \delta L_{t-1}^{FP} & \text{otherwise} \end{cases} \quad (30)$$

Firm profit from strategy $FP \in \{BI, BD, MI, MD\}$ is given for each type of firm by:

$$\begin{aligned} \pi_{i,t-1}^{BI} &= \mathbb{I}_{i,t-1}^S (B - R_{H,t-1}^k) + (1 - \mathbb{I}_{i,t-1}^S) (b - R_{L,t-1}^k), \\ \pi_{i,t-1}^{BR} &= \mathbb{I}_{i,t-1}^S (A_{i,t} - R_{H,t-1}^k) + (1 - \mathbb{I}_{i,t-1}^S) (-c), \\ \pi_{i,t-1}^{MI} &= \mathbb{I}_{i,t-1}^S (B - R) + (1 - \mathbb{I}_{i,t-1}^S) (-c), \\ \pi_{i,t-1}^{MR} &= \mathbb{I}_{i,t-1}^S (A_{i,t} - R) + (1 - \mathbb{I}_{i,t-1}^S) (-c), \end{aligned} \quad (31)$$

where $\mathbb{I}_{i,t}^S$ is an index tracking the success of firm i in innovative project P :

$$\mathbb{I}_{i,t}^S = \begin{cases} 1 & \text{with probability} \begin{cases} p_A & FP_i \in \{BD, MD\} \\ p_B & FP_i \in \{BI, MI\} \end{cases} \\ 0 & \text{with probability} \begin{cases} 1 - p_A & FP_i \in \{BD, MD\} \\ 1 - p_B & FP_i \in \{BI, MI\} \end{cases} \end{cases} \quad (32)$$

Ability for radical innovation evolves according to:

$$A_{i,t} = \max \{ A^H, \mathbb{I}_{i,t-1}^R A_{i,t-1} (1 + g) + (1 - \mathbb{I}_{i,t-1}^R) A_{i,t-1} \}, \quad (33)$$

where $\mathbb{I}_{i,t-1}^R$ tracks whether firm i was a radical innovator in $t-1$. In short, this means, regardless of the outcome, engaging in radical R&D will see the ability of a firm increase up to an upper limit given by A^H .

The total (illiquid) value of firm i in t :

$$W_{i,t} = \rho W_{i,t-1} + \pi_{i,t} \quad (34)$$

When $W_i < 0$ the firm goes through death and rebirth, with all firm specific variables being reinitialized:

$$W_{i,t} = W_{i,0},$$

$$A_{i,t} \rightarrow U(B, A^H),$$

$$L_{i,t}^{FP} = L_{i,0}^{FP}.$$

Appendix C - Figures

Figure 5: Distribution of population shares in 1000 simulations. Baseline parameters with higher cost of liquidation $c = 9$.

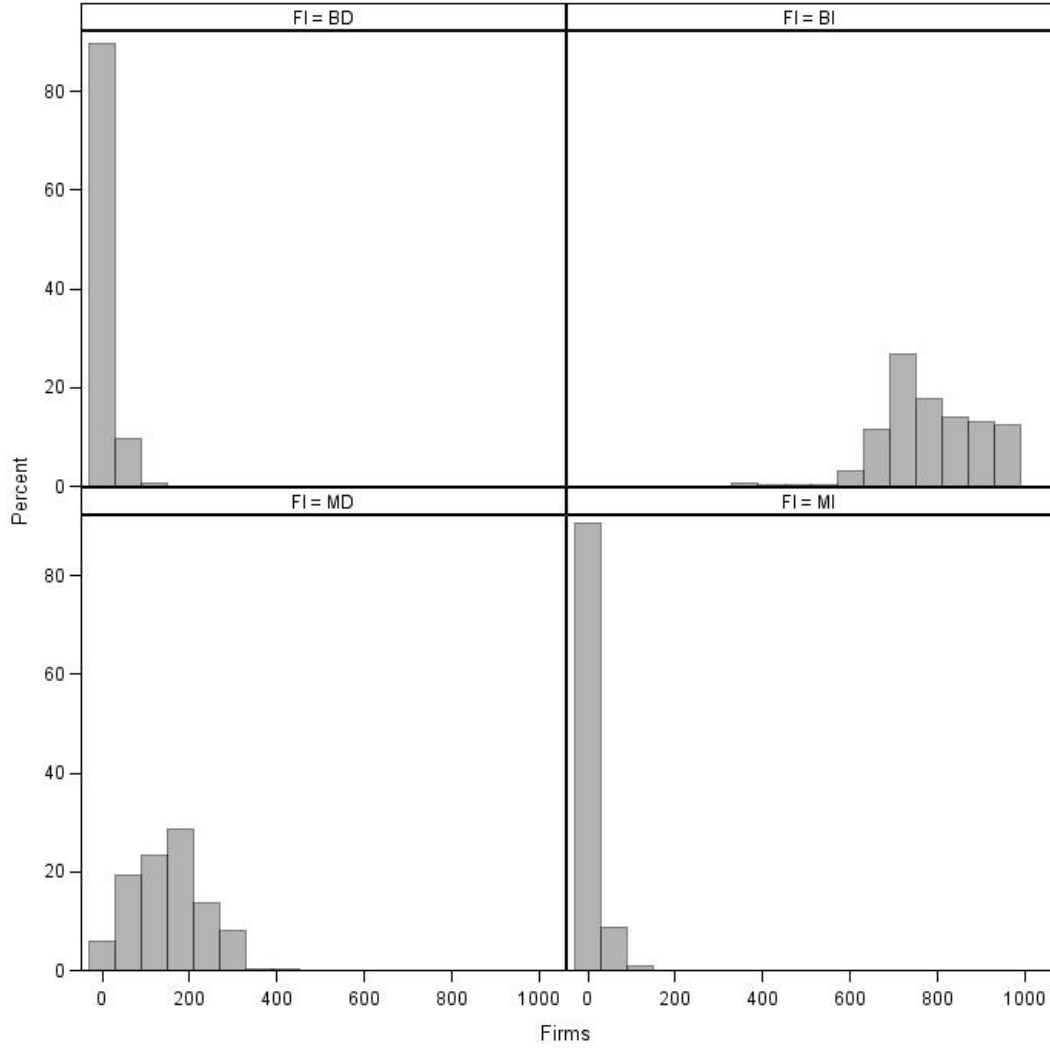


Figure 6: Baseline parameters with lower cost of liquidation $c = 7$.

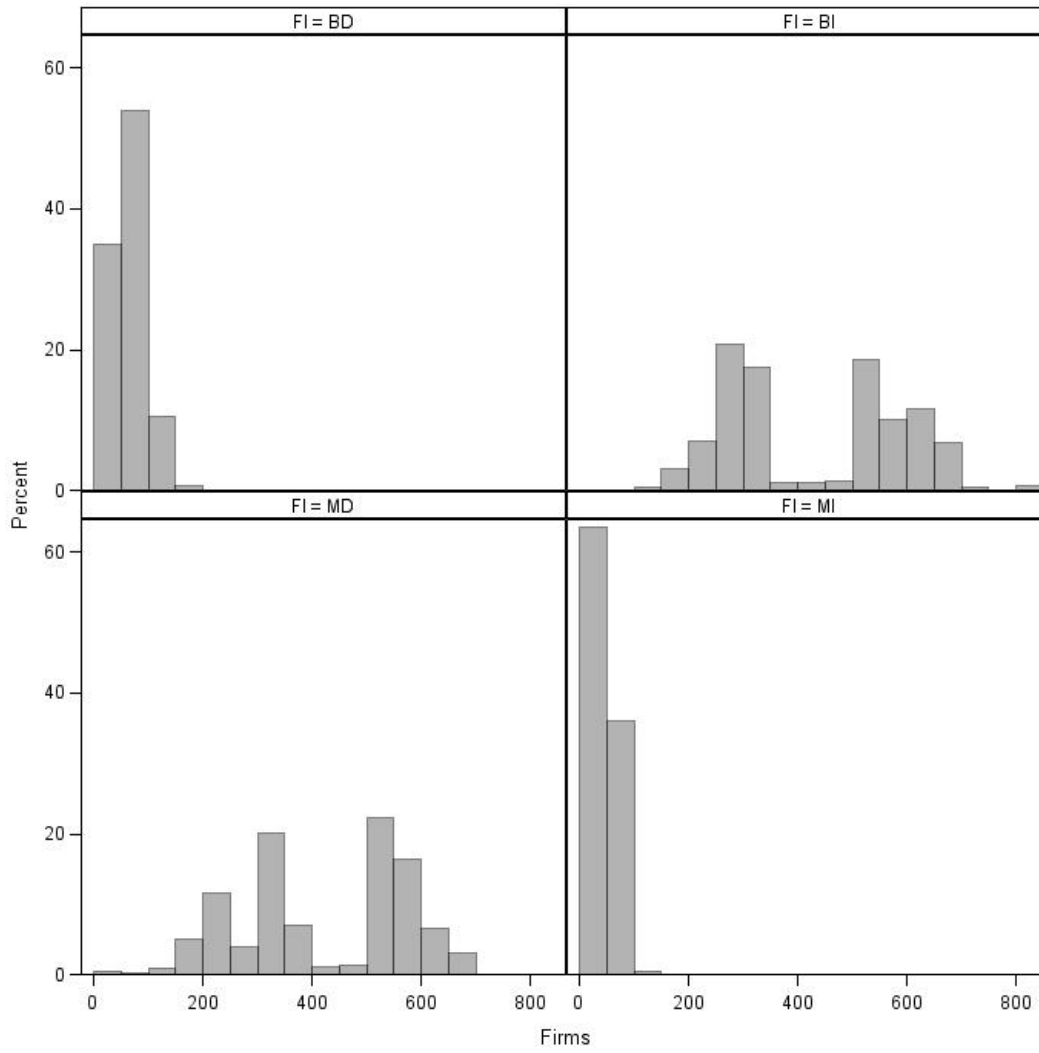


Figure 7: Distribution of population shares in 1000 simulations. Baseline parameters with lower cost of liquidation $c = 11$.

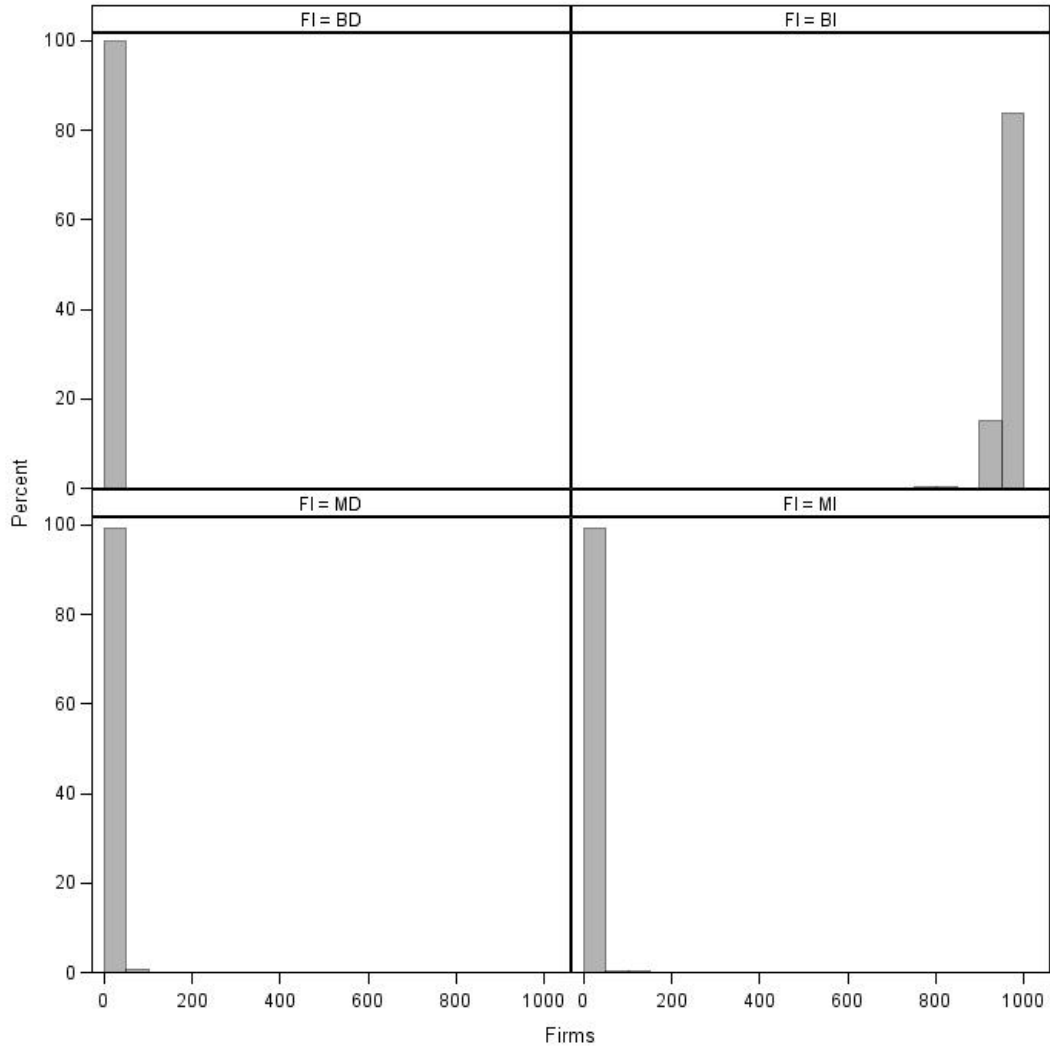


Figure 8: Baseline parameters with more menus $K = 16$

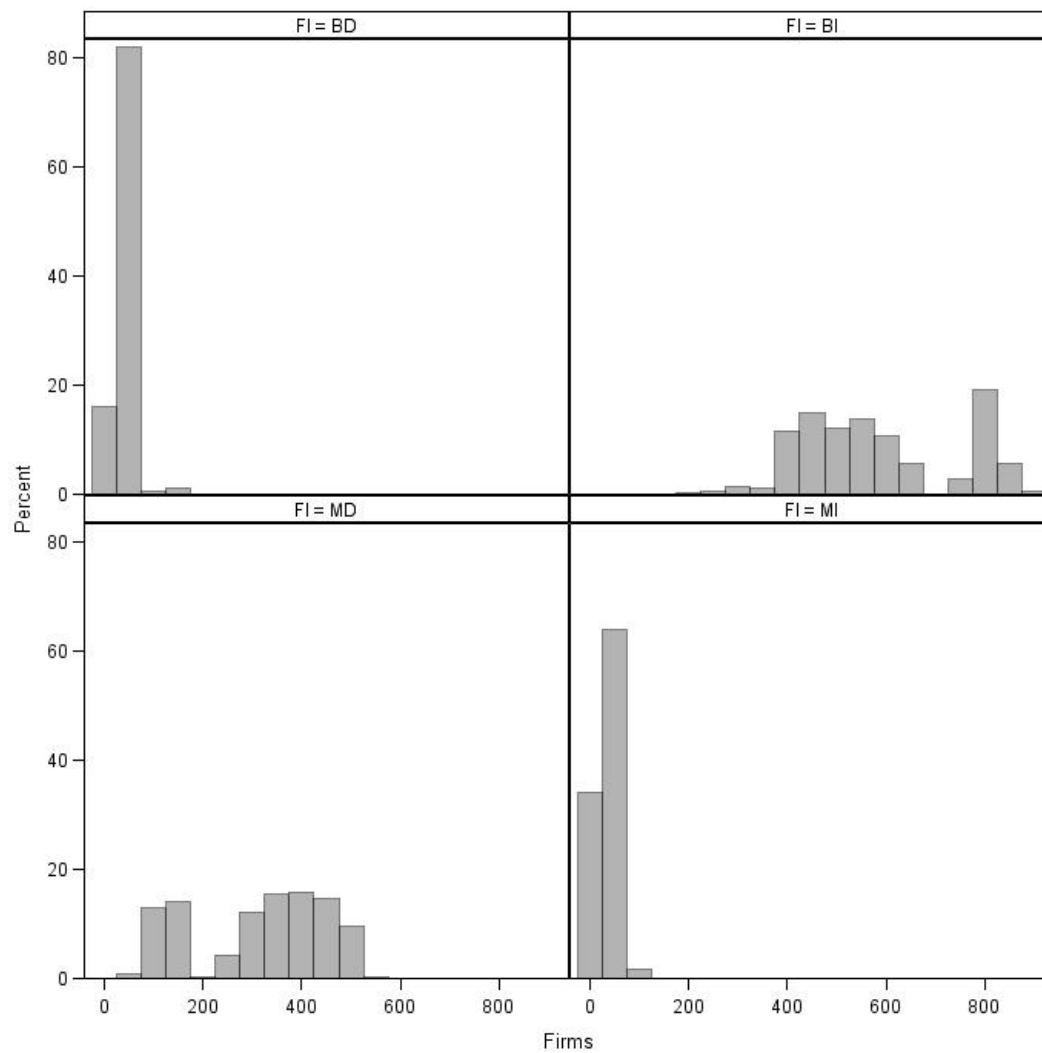


Figure 9: Baseline parameters with randomly generated menu set for each simulation: R_L drawn from $U(0, b)$ and R_H from $U(b, B)$.

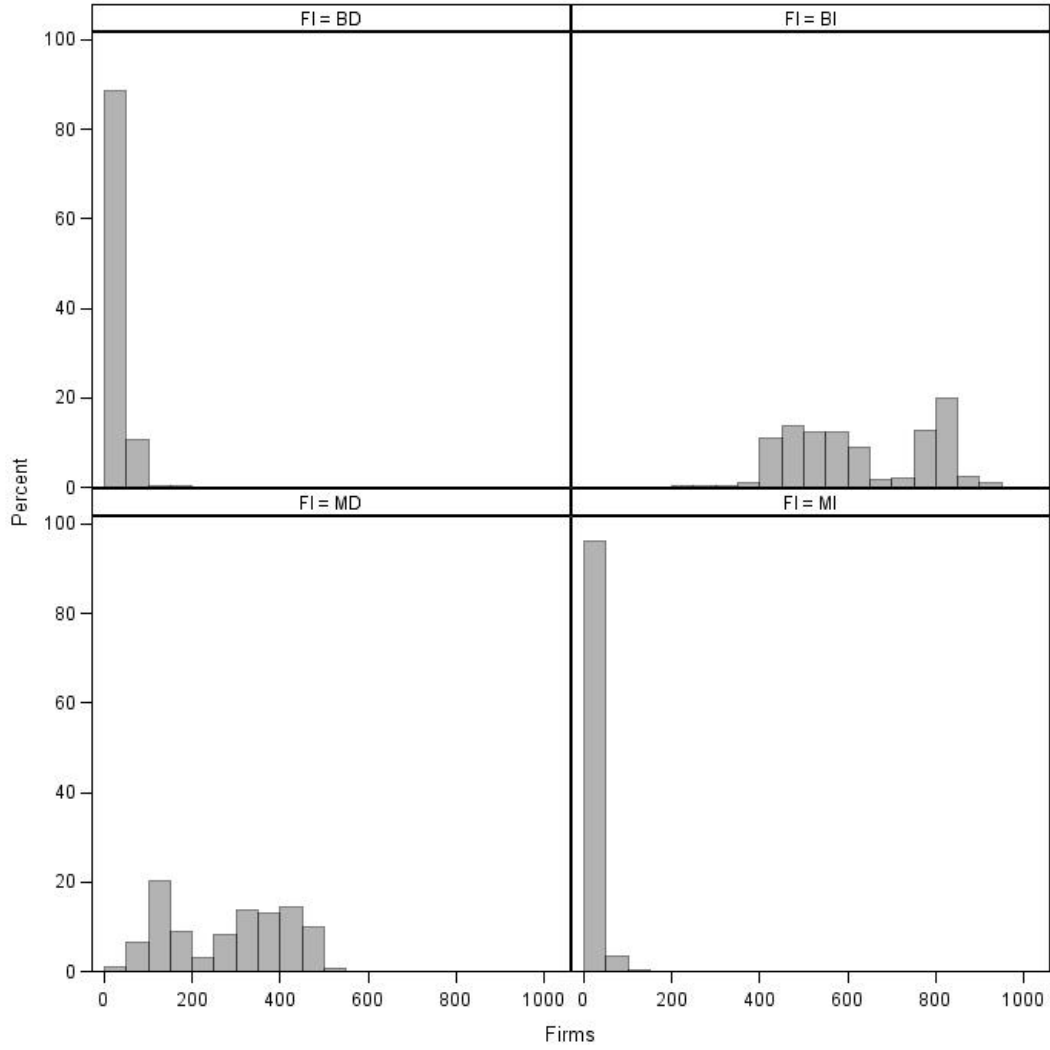


Figure 10: Distribution of population shares in 1000 simulations. Baseline parameters with different forgetfulness $\delta = 0.75$.

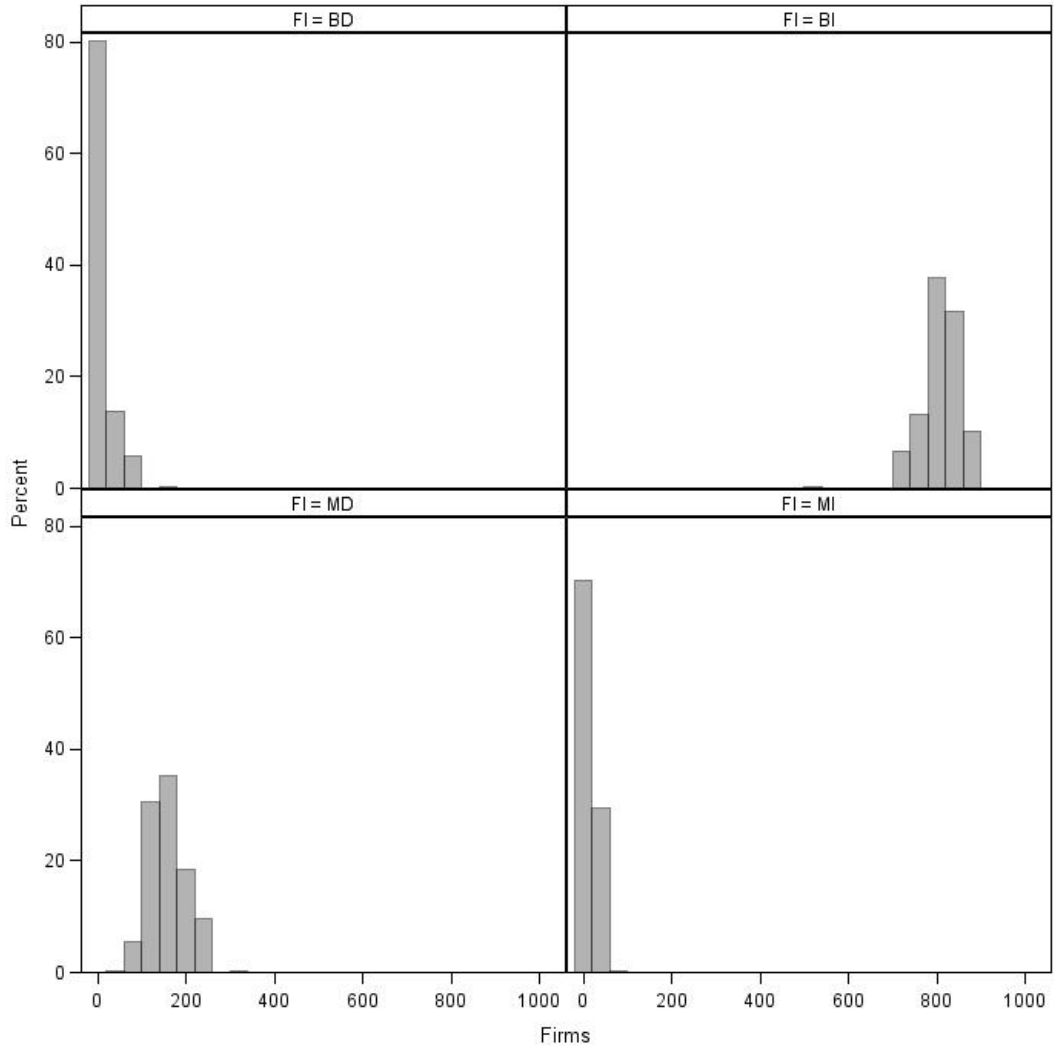


Figure 11: Distribution of population shares in 1000 simulations. Baseline parameters with different forgetfulness $\delta = 0.65$.

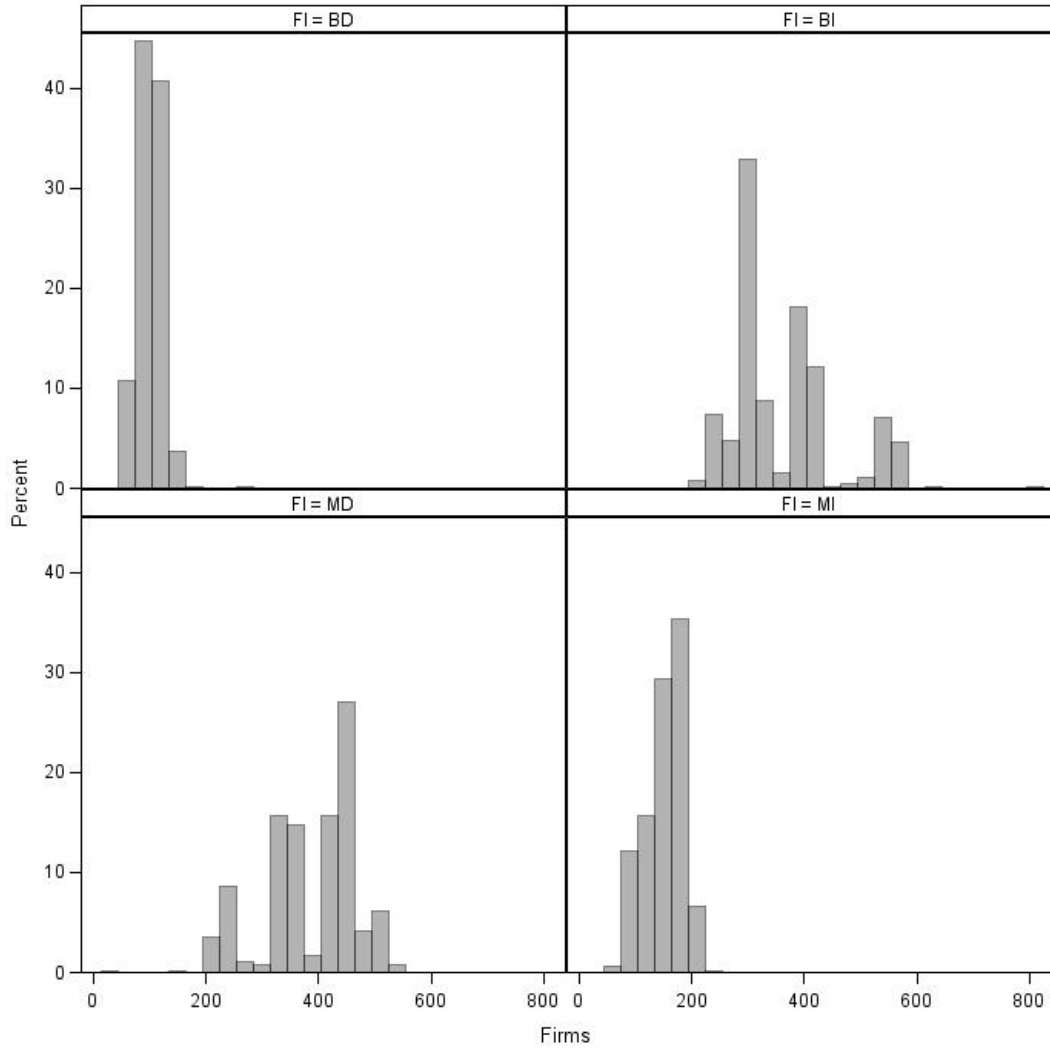
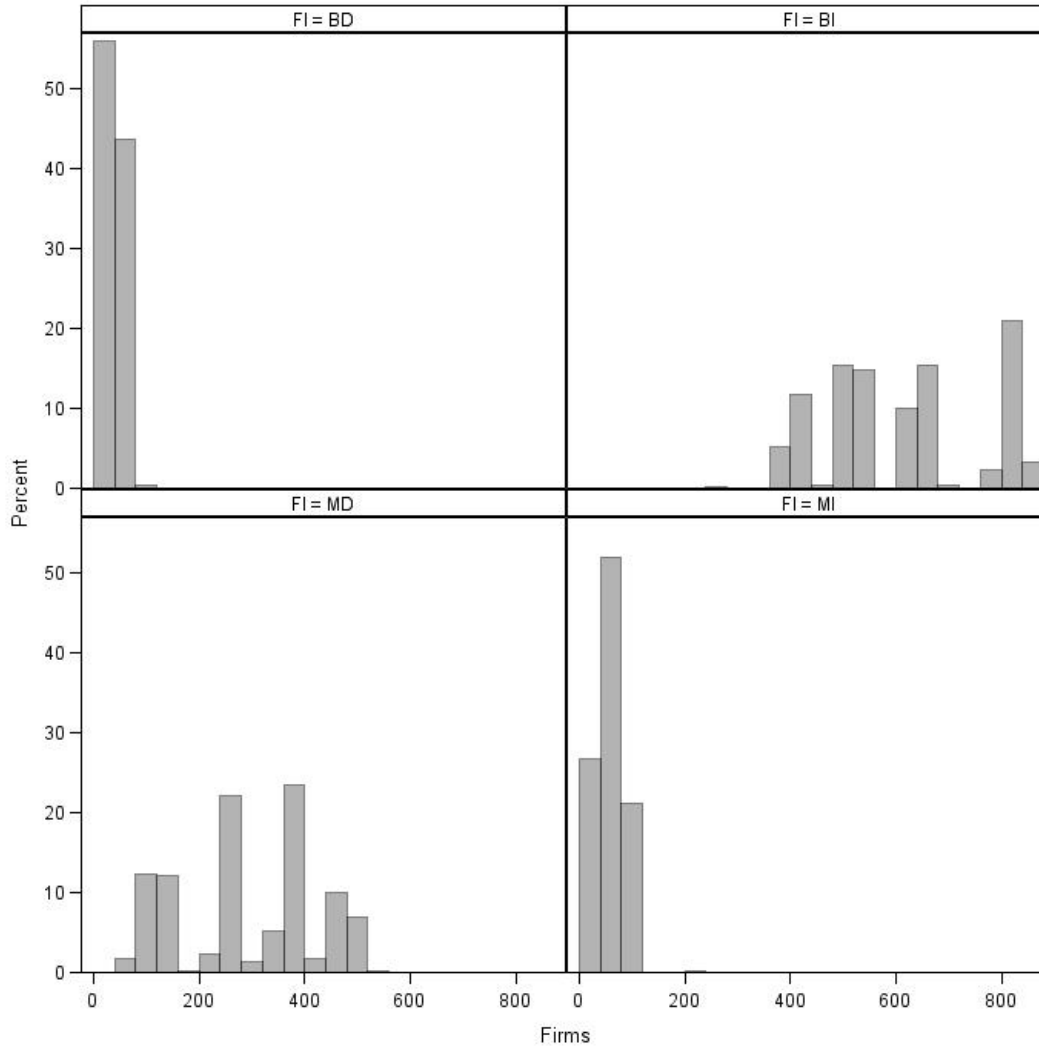


Figure 12: Distribution of population shares in 1000 simulations. Less steep learning curve - Higher Initial Reinforcements, $L_0 = 4$



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